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TRACKING AND DATA ACQUISITION SYSTEM FOR THE 1990's

VOLUME VIII

TDAS FREQUENCY PLANNING

DRAFT FINAL REPORT

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16. Abstract

Current planning calls for the TDAS to support new user and crosslink services, in addition to TDRSS - compatible services. TDRSS - compatible services would operate in current S-band and K-band channels used by TDRSS. New services, however can take advantage of technology advances at microwave and optical frequencies.

For augmented space-to-space services, 60 GHz and GaAs laser systems offer technical advantages, relative freedom from RFI, and a benign regulatory environment (i.e., minimal congestion and, in the case of 60 GHz, maximum regulatory support for TDAS-type services).

For TDAS earth-to-space and space-to-earth services, the 30/20 GHz band offers the best mix of technical and regulatory advantages. But use of these bands would have to be coordinated with the U.S. military.

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EXECUTIVE SUMMARY

Task 10 of the Tracking and Data Acquisition Study for the 1990's was chartered with four objectives:

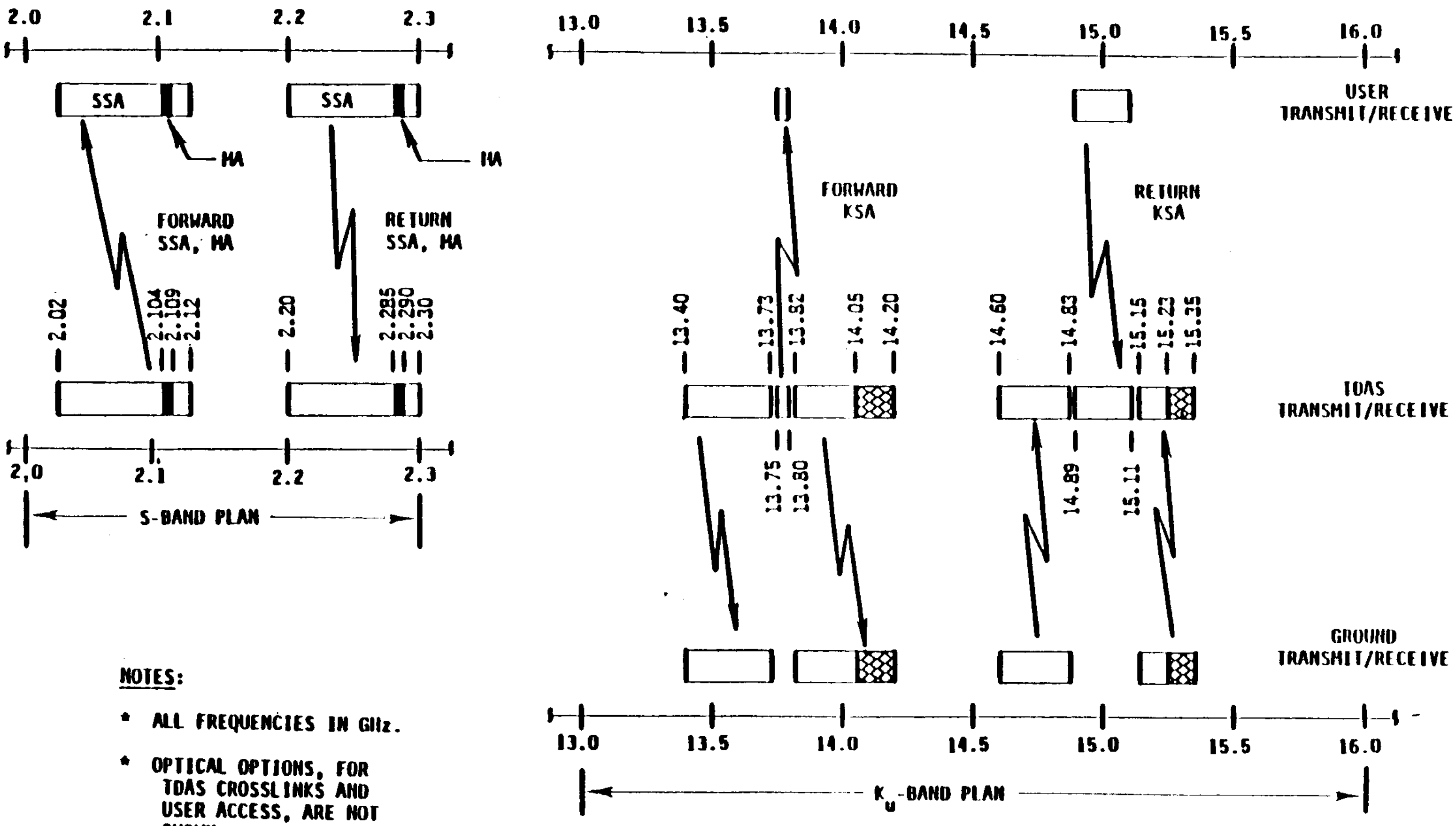
1. Definition of a TDAS frequency utilization plan
2. Definition of a Radio Frequency Interference (RFI) model
3. Definition of system survivability to RFI
4. Definition of requirements for robust operation in RFI.

These objectives were achieved, and two frequency management issues were identified as being important to TDAS. These issues address: (1) selection of frequency bands for TDAS space-to-space links; and (2) the application of 30/20 GHz technology to TDAS earth-space links. The primary frequency planning options for TDAS are summarized in Fiqures ES-1 and ES-2.

Frequency Bands for TDAS Space-to-Space Applications

With respect to frequency band selection for TDAS space-to-space links, the 60 GHz W-band (54.25 GHz - 58.2 GHz, and 59 GHz - 64 GHz) is the primary choice for the augmented single access service (WSA) supporting data rates from 50 kbps to 50 Mbps. W-band is also a fallback choice for TDAS space-to-space crosslinks if laser technology fails to mature in time for TDAS. A total bandwidth of 8.95 GHz is allocated for space-to-space applications between 54 GHz and 64 GHz. This allocation offers wide latitude for channel frequency assignment, and multiple access via frequency selection (FDMA). In addition, the 60 GHz center frequency supports large single-channel bandwidths desired by certain earth-observation spacecraft, and required for TDAS crosslinks. Atmospheric attenuation in excess of 10 dB over the entire band, and greater than 100 dB over more than 4 GHz, offers significant protection against terrestrial sources of RFI. No frequency less than 54 GHz offers this protection. Finally, the specified bandwidth (54.25 – 58.2 GHz and 59 - 64 GHz) is allocated to the inter-satellite service on a primary basis. Use of these frequencies would be supported and protected by U.S. and international regulatory policy.

FIGURE ES-1: S-BAND AND K_U-BAND FREQUENCY PLANNING OPTIONS FOR TDAS



NOTES:

* ALL FREQUENCIES IN GHz.
* OPTICAL OPTIONS, FOR TDAS CROSSLINKS AND USER ACCESS, ARE NOT SHOWN.

FREQUENCY BANDS NOT INCLUDED IN TDRSS PLAN.

FREQUENCY BANDS INCLUDED IN TDRSS PLAN

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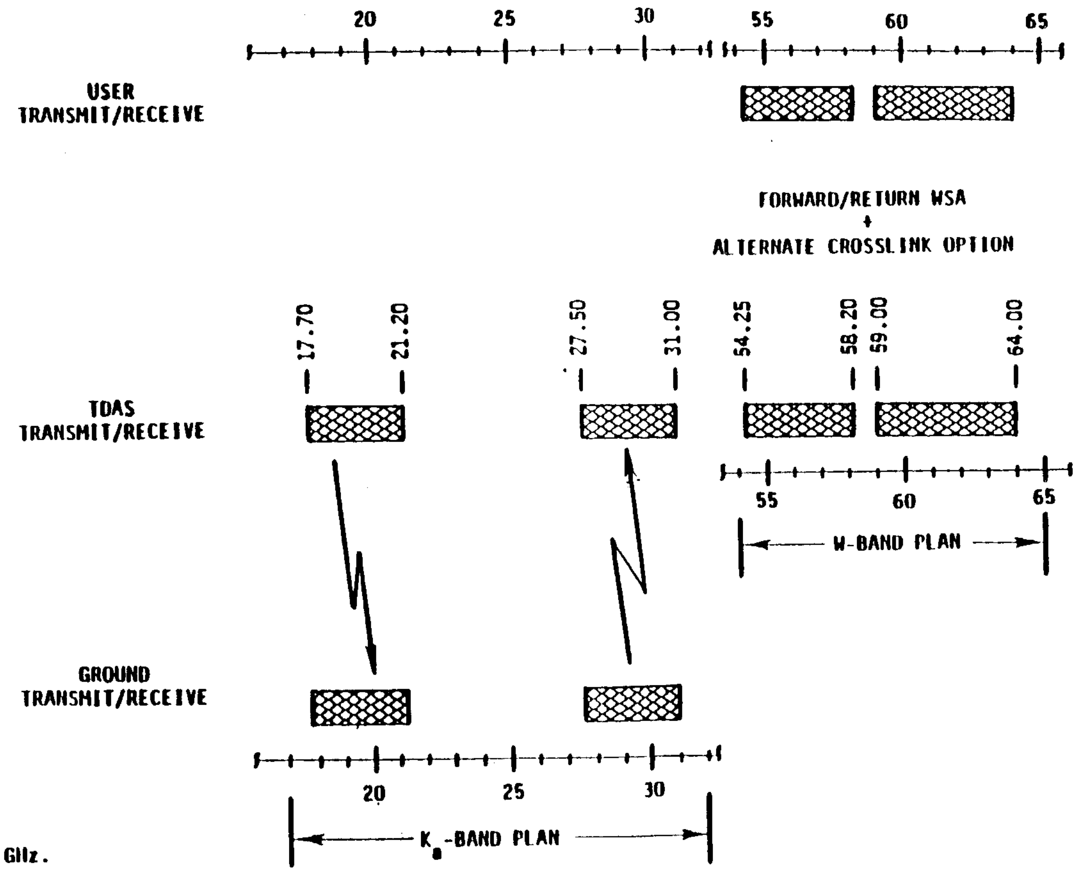
FIGURE ES-2: K_A-BAND AND W-BAND FREQUENCY PLANNING OPTIONS FOR TDAS



NOTES:

* ALL FREQUENCIES IN GHz.
* OPTICAL OPTIONS, FOR TDAS CROSSLINKS AND USER ACCESS, ARE NOT SHOWN.

FREQUENCY BANDS NOT INCLUDED IN TDRSS PLAN.

FREQUENCY BANDS INCLUDED IN TDRSS PLAN

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S-band and K-band channels are required for compatibility with TDRSS, but it would be nearly impossible to broaden TDRSS - authorized bands for support of augmented TDAS services. These bands are becoming increasingly congested, offer neglibible clear-sky attenuation ($\leq$ 1 dB), and provide limited regulatory support for operational space-to-space communication links. The lack of atmospheric protection against terrestrial RFI is a factor in the RFI problems anticipated to TDRSS. These bands offer insufficient flexibility for augmented TDAS services.

Lasers represent the primary technological choice for TDAS space-to-space cross-links and ultr-high rate single-access service. Their advantages are in large bandwidths/high data rates, heterodyne downconversion to microware frequencies with some receiver structures, and narrow beamwidth implying high gain. However, the high pointing accuracy requirement may represent a weight penalty for some user spacecraft.

Frequency Bands for TDAS Earth-Space Applications

The 30/20 GHz bands represent the most desirable option for TDAS Earth-space links. These bands offer 1GHz bandwidth, primary allocation status for all TDAS Earth-space services, and freedom from aeronautical-mobile users (a source of downlink RFI).* Lower frequency bands lack one or more of these desirable features. It would be possible to broaden TDRSS - authorized uplink and downlink bands for TDAS services. The U.S. Government Table of Frequency Allocations assigns an additional 100 MHz centered at 15.3 Ghz, and 150 MHz below 14.2 GHz, to Space Research. But these Ku-band allocations offer less bandwidth than K_a-band allocations, and only secondary allocation status. At frequencies above 30 GHz, technology is less mature

* The regulations proposed by the FCC/NTIA, and currently undergoing ratification, restrict government use of the 30/20 GHz bands for the fixed-satellite service to military users. This restriction is contained in Government footnote GYY4 to the U.S. Table of Frequency Allocations. As presently constituted, this footnote precludes TDAS use of 30/20 GHz. However, considering the anticipated sharing of TDAS among civilian and military users, it is reasonable to assume that negotiation through IRAC and the NTIA could open these bands for TDAS.

and rain-induce attenuation is greater. These considerations make 30/20 GHz the nominal best choice for TDAS Earth-space links. The 90/80 GHz bands represent an alternative to 30/20 GHz, but these bands require much larger margins (>> 10 dB additional margin for typical ground sites) to achieve equivalent link availability in the presence of rain.

SECTION 1

INTRODUCTION

This final report presents study results of Task 10 of the Tracking and Data Acquisition Study for 1990's. Task 10 was chartered with four objectives:

1. Definition of a TDAS frequency utilization plan
2. Definition of Radio Frequency Interference (RFI) model
3. Definition of system survivability to RFI
4. Development of requirements for robust operation in RFI

The goal is to provide information for engineering assessment of TDAS alternatives. The set of frequency band options is kept as broad as possible, providing maximum flexibility for future tradeoff analysis. All frequency bands that could be utilized in a TDAS are identified, and the characteristics of each band are defined. Potential RFI impact on TDAS survivability is discussed, and techniques for mitigating RFI to yield greater operational robustness are identified. Since the study effort documented herein will support future development of strawman TDAS designs, the discussion of RFI and mitigating techniques is intentionally kept general. The goal is to direct the system designer's attention to RFI scenarios that could affect particular designs, and highlight mitigation techniques that could be incorporated in response to RFI.

1.1 STUDY APPROACH

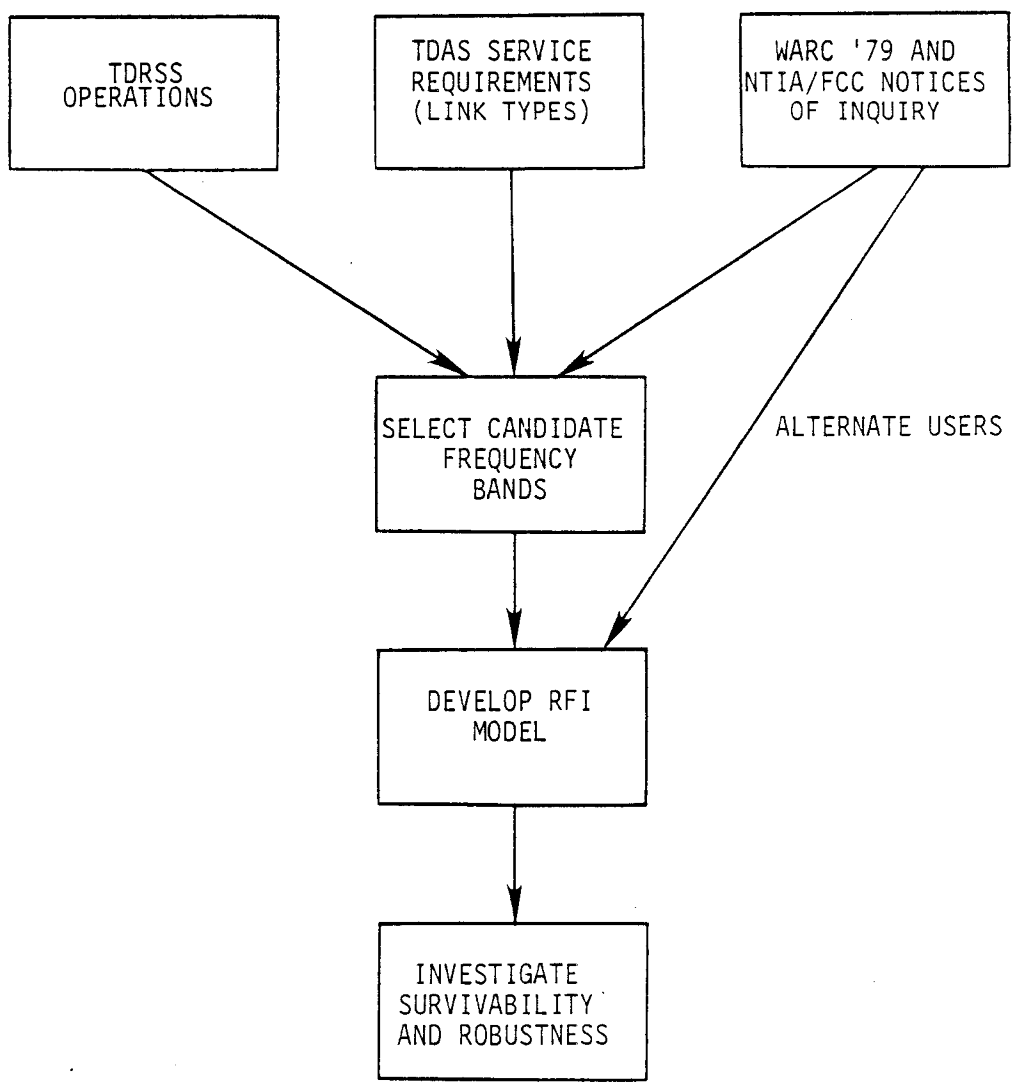
The study approach is illustrated in Figure 1-1. Primary source documents [1] - [5] were examined to identify candidate frequency bands for TDAS service. These bands are those currently employed for TDRSS operations, and those authorized for TDAS type service by proposed regulations of the NTIA/FCC. Additional bands in the optical region of the spectrum were identified based on technology projections [6], [7], [14].

FIGURE 1-1: STUDY APPROACH

OBJECTIVES OF STUDY

- TDAS FREQUENCY PLAN
- RFI MODEL
- SURVIVABILITY TO RFI
- REQUIREMENTS FOR ROBUST OPERATION

FLOW OF WORK



These candidate frequency bands were investigated with respect to survivability and robustness against natural and manmade radio frequency interference.

The object of the RFI investigation is to project vulnerability of TDAS to alternate radio sources and identify operating techniques that could mitigate projected interference.

1.2 FREQUENCY PLAN OPTIONS

The frequency plan options developed in Task 10 are summarized in Tables 1-1 and 1-2, where Table 1-1 addresses space-to-space link options and Table 1-2 addresses earth-space link options.

Table 1-1 collates frequency bands from TDRSS, candidate bands from references [2] - [5], and optical bands judged technologically mature by references [6], [7], [14].

The first two columns identify a frequency band and associated bandwidth, with band edges in GHz and bandwidth in MHz. There is a generally rising trend in allocated bandwidth as frequency increases, with all allocated bands above 25 GHz offering greater than 1 GHz of bandwidth.

Column 3 tabulates atmospheric attenuation on a zenith-looking Earth-space link. This is the <u>lowest</u> value of attenuation that would ever be experienced, with lower elevation angles or weather effects (i.e., rain) tending to increase overall attenuation. By appropriate selection of a frequency band, atmospheric attenuation can be utilized to protect space-space links from terrestrial RFI emitters. Frequency bands with this characteristic exist above 50 GHz.

Column 4 identifies frequency bands allocated for the full range of TDAS space-to-space applications. These applications include space research, space operations, data return for earth exploration, data return for meteorological observations, and other unspecified inter-satellite links. General-purpose bands, which support all these applications equally, are

TABLE 1-1

AVAILABLE FREQUENCY BANDS[1]

SATELLITE-SATELLITE SERVICE

SUMMARY

FREQUENCY BAND	BANDWIDTH (MHz)	CLEAR-SKY ATMOSPHERIC ATTENUATION[2] (dB)	ALLOCATED FOR ALL TDAS SERVICES	PRIMARY ALLOCATION
2.020-2.123[3]	103	<.1	NO	NO
2.20 - 2.30[4]	90	<.1	NO	NO
13.4 - 14.00	800	<.1	NO	NO
14.0 - 14.20	200	<.1	NO	NO
14.5-14.715 14.715-15.1365 15.1365-15.35	850	<.1	NO	NO
23-23.55	550	≈1	YES	YES
25.25-27 27-27.5	2250	≈1	NO	NO
54.25-58.2	3950	10-100	YES	YES
59-64	5000	50-100	YES	YES
116-126 126-134	18000	1-100	YES	YES
170-174.5 174.5-176.5 176.5-182	12000	5-90	YES	YES

1 THIRD AND FOURTH NOTICES OF INQUIRY IN THE MATTER OF IMPLEMENTATION OF THE FINAL ACTS OF THE WORLD ADMINISTRATION RADIO CONFERENCE (GENEVA, 1979).

2 FROM CRANE, 1971, 174 REPRODUCED IN J.J. SPILKER, JR., DIGITAL COMMUNICATIONS BY SATELLITE (PRENTICE-HALL, INC., ENGLEWOOD CLIFFS, 1977) P. 170.

3 TDRSS FORWARD S-BAND LINKS ARE NOT SUPPORTED IN THE PROPOSED TABLE OF U.S. GOVERNMENT ALLOCATIONS.

4 CONSISTENT WITH WARC '79, THE UPPER 10 MHZ OF THIS BAND (2.29-2.30 GHZ) WOULD ONLY BE USED BY TDAS TO SUPPORT DEEP-SPACE PROBES WHILE STILL IN THE VICINITY OF EARTH.

TABLE 1-1

AVAILABLE FREQUENCY BANDS

SATELLITE-SATELLITE SERVICE

SUMMARY (CONT)

FREQUENCY BAND (GHz)	BANDWIDTH (MHz)	CLEAR-SKY ATMOSPHERIC ATTENUATION[2] (dB)	ALLOCATED FOR ALL TDAS SERVICES	PRIMARY ALLOCATION
185-190	5000	(TBD)	YES	YES
OPTICAL -532 nm -832 nm -1060 nm	>10000	< 5 (NOTE 6)	(NOTE 5)	(NOTE 5)

5 OPTICAL BANDS ARE NOT ADDRESSED IN CURRENT OR PROPOSED REGULATIONS

6 LEE, SCHROEDER, AND CLANG, REF [9]

TABLE 1-2

AVAILABLE FREQUENCY BANDS[1]

EARTH-SATELLITE SERVICE

SUMMARY

FREQUENCY BAND (GHz)	BANDWIDTH (MHz)	AERONAUTICAL-MOBILE ALLOCATION	TDAS SERVICES ALLOCATED	TDAS ALLOCATION
0.137-0.138	1	NONE	DOWNLINK	PRIMARY
0.40015-0.401 0.401-0.402 0.402-0.403	2.85	NONE	UPLINK + DOWNLINK	PRIMARY EXCEPT 0.402-0.403
0.460-0.470	10	NONE	DOWNLINK	SECONDARY
1.427-1.429	2	PRIMARY	UPLINK	PRIMARY
1.99-2.11	2	NONE	UPLINK	SECONDARY
2.2-2.9	9	PRIMARY	DOWNLINK	PRIMARY
7.19-7.235	45	NONE	SOME UPLINK	PRIMARY
8.025-8.175 8.175-8.215 8.215-8.4 8.45-8.5	475	SECONDARY	DOWNLINK	PRIMARY
13.25-13.4 13.4-14.0 14.0-14.2	950	PRIMARY	SOME UPLINK + ALL DOWNLINK	SECONDARY
14.5-14.7145 14.7145-15.1365 15.1365-15.35	850	PRIMARY	SOME UPLINK SOME DOWNLINK	SECONDARY
20.2-21.2	1000	NONE	DOWNLINK	PRIMARY[2]

[1] SECOND, THIRD AND FOURTH NOTICES OF INQUIRY IN THE MATTER OF IMPLEMENTATION OF THE FINAL ACTS OF THW WORLD ADMINISTRATION RADIO CONFERENCE (GENEVA, 1979)

[2] CURRENTLY LIMITED TO MILITARY APPLICATIONS BY FOOTNOTE GYY4 TO THE U.S. GOVERNMENT TABLE OF FREQUENCY ALLOCATIONS.

TABLE 1-2

AVAILABLE FREQUENCY BANDS

EARTH-SATELLITE SERVICE

SUMMARY (CONT)

FREQUENCY BAND (GHz)	BANDWIDTH (MHz)	AERONAUTICAL-MOBILE ALLOCATION	TDAS SERVICES ALLOCATED	TDAS ALLOCATION
30.0-31.0	1000	NONE	UPLINK	PRIMARY[2]
39.5-40.5	1000	NONE	DONWLINK	PRIMARY[2]
42.5-43.5	1000	NONE	UPLINK	PRIMARY
47.2-50.2	3000	PRIMARY	UPLINK	PRIMARY
65-66	1000	SECONDARY	SOME UPLINK SOME DOWNLINK	PRIMARY
71-74 74-75.5	4500	PRIMARY	UPLINK	PRIMARY
81-84	3000	PRIMARY	DOWNLINK	PRIMARY
92-95	3000	PRIMARY	UPLINK	PRIMARY
102-105	3000	PRIMARY	DOWNLINK	PRIMARY
149-150 150-151 151-164	5000	PRIMARY	DOWNLINK	PRIMARY
202-217	15000	PRIMARY	UPLINK	PRIMARY
231-235 235-238 238-241	10000	PRIMARY	DOWNLINK	PRIMARY
265-275	10000	PRIMARY	UPLINK	PRIMARY

[2] CURRENTLY LIMITED TO MILITARY APPLICATIONS BY FOOTNOTE GYY4 TO THE U.S. GOVERNMENT TABLE OF FREQUENCY ALLOCATIONS

tabulated with a "YES". Other bands, for which service is generally restricted to one of the application types noted above, are tabulated with a "NO". For example, TDRSS K-band services are located in bands allocated on a secondary basis to space research. NASA depends on frequency management and coordination, with external agencies and entities, to maintain these bands without interference. The management risk for TDAS can be reduced if new services (i.e., those not constrained to be compatible with TDRSS) are located in general-purpose bands such as "Intersatellite" (for space-to-space connectivity) and "Fixed-Satellite" (for space-to-earth connectivity).

Column 5 describes the priority of the relevant inter-satellite allocations relative to other services that share the band. Allocations are either primary or secondary, with primary services given preference in the event of conflict. For example, with TDAS operating as a primary service, and with RFI from a secondary service, the secondary service would be required to modify its operations and cease interference. Alternatively, TDAS would be required to modify operations if the positions were reversed.* The security value of a primary allocation is clear.

Optical wavelengths are candidates for TDAS inter-satellite service. These wavelengths are currently outside the scope of national and international allocations, and therefore available for any application. The draft frequency plan identifies optical wavelengths as suitable for space-space applications only--weather affects make optical wavelengths unsuitable for fixed-satellite service in an operational system such as TDAS.** Current optical technologies that show promise for near-term space-qualification are in the infrared and blue-green regions of the spectrum [6], [14]

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* The order of assignment is unimportant in cases of interference across allocation levels. But with interference among services at the <u>same</u> allocation level, the oldest service has preference.

** Cloud-induced losses > 5 dB can be expected approximately 85% of the time [9], page 95.

Viewed as a whole, Table 1-1 indicates that allocated bands above 50 GHz are desirable in many respects from a frequency management perspective. These bands offer primary allocations for all TDAS space-to-space links, with bandwidths in excess of 1 GHz and atmospheric protection against terrestrial RFI emitters. Selected bands below 50 GHz may be suitable for special applications.

Table 1-2 collates earth-satellite bands from TDRSS and proposed regulations. Columns 1 and 2 are similar to Table 1-1, describing frequency band and bandwidth for each set of adjacent allocated bands. For example, three adjacent bands from 0.40015 GHz to 0.403 GHz have a combined bandwidth of 2.85 MHz. Whereas the lowest frequency for space-to-space applications was 2.02 GHz, earth-space allocations extend down to 137 MHz. The relatively narrow bandwidths at lower frequencies make these bands unsuitable for trunking or high data rate downlinks; but they may be used for special purpose and command links.

Column 3 identifies the allocation level of the aeronautical-mobile service. This service presents a threat to the TDAS-ground downlink, since an airborne platform could inject high-level RFI directly into the mainbeam of the ground receive antenna. Legal precedence over the aeronautical service is highly desirable, to protect against this form of unintentional interference. Column 3 may be compared to column 5 to determine the precedence relationship. Bands not allocated to the aeronautical-mobile service ("NONE" in column 3) are most preferred in this regard. (See Section 3 for a more complete discussion of this problem).

Columns 4 and 5 identify TDAS services that can be supported and their level of allocation. For example, the band 137-138 MHz is allocated to all downlink services on a primary basis. The terms "SOME UPLINK" and "SOME DOWNLINKS" identify specific allocations in the related band. The 7.19-7.235 GHz band, for example, is limited to uplink applications in the space research service. This band would be nominally off-limits for space operations, earth-exploration, etc. The exact limitations are identified in Section 2, Table 2-4.

In the 20-40 GHz range, government use of all bands allocated to services applicable to TDAS is limited to military applications by footnote GYY4 (U.S. Table of Frequency Allocations). However, cooperation among government users of the spectrum is possible, and probably desirable. This is particularly true for TDAS, where the military and all other users would benefit through shared use of optimal resources.* This issue highlights the need for ongoing frequency management at the policy level. Current decisions being made by frequency management policy makers will determine the availability of the 30/20 GHz band to TDAS applications.

1.3 SURVIVABILITY AND ROBUSTNESS AGAINST RFI

In the context of this report, the term Radio Frequency Interference (RFI) is restricted to unintentional interference to TDAS communication links by electromagnetic radiation. This includes natural and manmade sources. In this context, the terms "survivability" and "robustness" should be viewed in the following qualitative sense: A survivable system is able to operate in any anticipated RFI environment. A robust system, on the other hand, provides some level of resistance and graceful degradation in the presence of harsh RFI environments without guaranteeing a specific level of performance.

For the purpose of long rang planning four classes of radio frequency interference (RFI) can be identified:

1. Natural sources. The sum emits electromagnetic radiation at all frequencies of interest to TDAS, and therefore represents an important source of RFI for selected geometries.

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* For a given weight and power limitation, shared channel resources should result in greater capacity and availability for all users, relative to a system with physically duplicated components at different frequency bands.

2. Self-interference. In system configurations where several user satellites (USATs) share a common operating frequency, self-interference could lead to unacceptable degradation of user signaling.

3. Other civilian services. Many frequency bands that are physically appropriate for TDAS are allocated jointly to several radio services. In cases where a non-TDAS service is granted higher allocation status relative to TDAS, degradation of TDAS signaling could take place without regulatory remedy.

4. Military services. Certain strategic and tactical radars represent high-power sources of unintentional RFI. These sources currently represent a degradation with respect to TDRSS frequency bands which can be expected to become more severe in the future.

TDAS survivability to these RFI sources is a function of projected system architecture, spacecraft design, user mission profiles and time of year (particularly with respect to solar outages). At the current study level, a preliminary discussion of survivability is therefore limited to potential RFI scenarios. Man-made RFI emitters are assumed to fully utilize the RF spectrum consistent with proposed FCC/NTIA regulations (based on WARC '79 and the FCC Notices of Inquiry in response to the WARC).

TDAS survivability and robustness can be improved by incorporation of elements from the following list:

1. Alternate routing capability to bypass links with temporary RFI;

2. Frequency band selection to take advantage of atmospheric attenuation;

3. Coding/interleaving optimized for RFI;

4. Improved hardware to provide higher transmitt EIRP or receive G/T, and the use of adaptive techniques such as antenna pattern nulling;

5. Command verification protocols to trap undetected errors in forward link commands.

These techniques are related to particular sources of RFI in the discussion below, and addressed in greater detail in Section 4 of this report.

Solar RFI causes a "sun transit outage" which occurs when pointing angles from a receiving antenna to a transmitting satellite and the sun are so near coincidence that both are within the receiving antenna beamwidth. The receiving antenna can be at an earth station or on a satellite. Solar RFI is paricularly troublesome on and around the spring and autumn equinoxes, when satellites in near-equatorial orbits have high probability of achieving colinearity with the sun. In addition, spacecraft in nonequatorial orbits have windows of vulnerability which become larger in time as orbital inclination increases.

During any solar/satellite conjunction*, reliable communication is impossible during actual colinearity. But at the cost of the increased spacecraft power/weight, the effects of conjunction can be mitigated be improved transmit EIRP, receive G/T, or usage of lower-rate FEC coding. An alternative approach is maintenance of a dual-routing or multiple-routing capability. Since solar conjunctions are easily predicted for all spacecraft and spacecraft-earth terminal pairs, alternative routing through the multi-satellite TDAS network can yield signficant gains in channel availability. The cost here is in ground software complexity, where additional constraints would be imposed on the TDAS scheduling algorithms.

* A receiving station views a transmitting spacecraft as well as the sun in the high-gain portion of its antenna beam.

RFI caused by self-interference can become a problem in system configurations that rely on beam discrimination to separate transmissions from various user spacecraft. RFI may exist when a TDAS satellite attempts to service two user spacecraft with small angular separation (as viewed from TDAS). Appropriate scheduling techniques can mitigate this problem, by grouping user spacecraft in sets such that members of a set are angularly separate from one another at the time of service. TDAS then services one set at a time, without self-interference. An important element of such scheduling is the alternative routing capability discussed above. Simulation would be desirable to determine the improvement available with these techniques for a particular TDAS configuration and user constellation. Other mitigating techniques include improved receiver antenna gain, improved modulation techniques that resist interference (i.e., coding), or techniques that provide diversity against it (i.e., FDMA, TDMA, CDMA, polarization diversity, etc.).

Lawful interference from other civilian services is due to the shared allocation strategy pursued by FCC/NTIA. All frequency bands of interest are jointly allocated to several user classes. For example, frequency bands allocated to space-earth downlink operations may be simultaneously allocated to fixed and mobile terrestrial user services.

Operating frequencies should be chosen to minimize the chance of conflict as well as maximize the TDAS precedence level should conflicts occur -- thus insuring that TDAS services are protected with the force of regulation. The ideal situation is a primary allocation for TDAS-type service, with all other services allocated on a secondary basis only. Less desirable situations are shared allocations on a primary basis to TDAS as well as other services, or secondary allocation status to TDAS - type services. Regulatory precedence for TDAS is most desirable on space-to-space link allocations, where variable geometries among TDAS and user spacecraft permit interference from virtually all terrestrial locations. Space-space links can be protected by judicious selection of frequency bands in the atmospheric absorption regions around 60 GHz. Attenuation of terrestrial emissions in excess of 50 dB

can be achieved by careful band selection, making the question of terrestrial RFI virtually moot. Up/down link allocations cannot take advantage of atmospheric attenuation, but ground equipment design can mitigate most problems of manmade RFI. A combination of high-power, high gain uplink transmission can protect the uplink, while the high gain receiver possibly coupled with sidelobe suppression equipment can protect the downlink. The major threat with respect to downlink RFI becomes the mobile aeronautical service, which could inject RFI from an airborne transmitter directly into the main beam of the TDAS ground receiver. A primary allocation status for TDAS is the most straightforward mitigation technique in this case, but certain modulation techniques may prove effective with further research. In particular, coding and interleaving may prove effective depending on projected aircraft dynamics and the radio operation regime of airborne users.

Military services of the United States and foreign countries employ radar transmitters that pose an unintentional hazard to TDAS. Main beam-to-main beam coupling from strategic radars can exist regardless of emitter location on the earth's surface. Tactical radars, with their relatively low-elevation scanning angles, are chiefly a problem near the earth's limb (as viewed by the receiving spacecraft). Space-to-space links are particularly vulnerable to radar emissions, due to the relative spacecraft motions that bring different parts of the earth into view of the receiving spacecraft. Characterization of this hazard is difficult, particularly with respect to current and future planning of foreign nations. In view of these difficulties, and the documented impact on TDRSS [11], it is prudent to incorporate techniques to guarantee TDAS robustness. These techniques include:

1. Alternative routing capability.
2. Band selection to optimize atmospheric screening.
3. High-gain receive antennas to minimize coupling.
4. Coding/interleaving optimized for projected RFI.

Since most ground terminals are at inland locations within CONUS, and most U.S. radars are located near the coasts,* up/down links are less vulnerable to radar interference than space-to-space links. Coastal and near-coastal sites may experience vulnerability to U.S. tactical radar emissions as a function of frequency band, ground site equipment, TDAS orbital location, terrestrial geography in the vicinity of the ground site, and radar operating regime.

With respect to the general RFI problem described above, command verification protocols can provide significant operational robustness even with degradation of data. Command verification involves echo-back of commands to the originating authority, where the echo is compared to a copy of the original command. If the echo matches the copy, a go-ahead signal is transmitted. This signal triggers execution of the command, which was read but not immediatly implemented by the receiving satellite. Command cycle time is approximately tripled due to three transmissions instead of one (initial command, echo-back and go-ahead).** Command verification also involves an increase in spacecraft command processor complexity -- to handle echo-backs, latching of commands, verification timeout periods, etc. With these costs, however, the probability of uncommanded spacecraft action is virtually eliminated.

1.4 ORGANIZATION OF REPORT

This report is organized in 4 sections as follows:

Section	CONTENTS
1	Introduction. Discusses methodology, major conclusions in the form of frequency plan options, and a description of report organization.
2	Candidate Bands for TDAS Service. Discusses all bands authorized for TDAS inter-satellite and fixed-satellite service.

* Foreign radars are naturally excluded from CONUS.

** Processor delays are assumed negligible relative to the propagation delays.

3	Projected Survivability to RFI. Projects impact of RFI on various bands identified in Section 2, via a geometric interference model and alternate services authorized in the International and U.S. Tables of Frequency Allocations.
4	Techniques for Robust Operation. Discusses modulation, architectural and operational techniques capable of mitigating RFI.

SECTION 2

CANDIDATE BANDS FOR TDAS SERVICE

This section identifies candidate frequency bands for TDAS use. These bands are suggested by three sources:

1. Current TDRSS frequency utilization plan.

2. Proposed regulations of the NTIA/FCC, consistent with the final acts of the WARC (Geneva, 1979).

3. Technology projections for laser-based communication systems.

The intent at this stage is to identify a broad set of frequency bands suitable for TDAS, maintaining sufficient latitude to allow engineering tradeoffs at a later date. The union of all frequency bands suggested by the above three sources is developed in this section -- no effort is made to eliminate candidate bands on the basis of engineering or economic feasibility. However, issues of concern are highlighted in the text wherever implementation of a particular frequency band would encounter known obstacles. The contributions of the above sources are discussed in turn below.

2.1 TDRSS FREQUENCY UTILIZATION PLAN

The TDRSS frequency bands are identified in Table 2-1. These bands represent proven technology and can be made interoperable with TDAS to support transition service. Offsetting these advantages, TDRSS bands will be affected by RFI from man-made terrestrial emitters (Section 3). These emitters exist at S-band and K-band, affecting forward and return link service between TDRSS and user satellites. The problem is currently most severe at S-band, where signigicant deployments of air defense radars share the TDRSS bands. Main-beam-to-main-beam coupling will occur with relatively high probability.

TABLE 2-1

TDRSS FREQUENCY BANDS

Service	Frequency[1] (MHz)
Forward Links	
MA	2103 - 2110
SSA	2020 - 2123
KSA	13748 - 13802
Return Links	
MA	2284 - 2290
SSA	2200 - 2300
KSA	14888 - 15119
Composite Downlink[2]	13401 - 14044
Composite Uplink[2]	14599 - 15226

1 Frequency band edges are given to the nearest MHz, as sensed by the recipient.

2 Composite bandwidths for uplink and downlink are not fully occupied.

K-band interference will be less severe because of limited deployment of K-band equipment, the intermittent operating regime of may of these radar sets, and the application of these radars to primarily tactical missions. The relatively low main-beam elevation angle of these tactical radars implies low probability of main-beam-to-main-beam coupling except when TDRSS illuminates territory near the earth's limb.

Many of TDRSS's anticipated problems with RFI stem from a lack of knowledge of these RFI sources when the TDRSS design was finalized. This yielded a system configuration that is suboptimum for the actual environment. With proper engineering design, much of this impact could be avoided in a follow-on TDAS. On the other hand, the deployment level, signal strength and operating regimes of military radars are likely to increase in the coming decade. Any TDAS design based on these frequencies for TDAS-USAT link support must consider this issue carefully.

The uplink/downlink TDRSS band is currently unaffected by K-band radar RFI since these links terminate well within the interior of CONUS. This offers protection against U.S. tactical K-band radars, which are typically deployed outside of CONUS. With respect to TDAS, system configurations with alternative ground sites near U.S. shoreline may experience some degradation on K-band uplinks and downlinks as well.

2.2 PROPOSED ALLOCATIONS DUE TO WARC '79

The FCC has published four Notices of Inquiry (NOI's) in the matter of implementation of the final acts of the World Administrative Radio Conference held in Geneva in 1979 [2] - [5]. These Notices of Inquiry* coordinate the positions of the FCC and the NTIA. The FCC** regulates the U.S. nongovernment telecommunications community. The NTIA*** coordinates

* Henceforth, the term "Notice(s) of Inquiry" should be construed as referring to one (or several) of references [2] - [5].

** FCC = Federal Communications Communication

*** NTIA = National Telecommunication and Information Administration.

the U.S. government telecommunications community (this includes uses of the radio spectrum for purposes other than communication, such as radiolocation (radar)). These documents have been ratified by the Senate and are awaiting Presidential signature. They represent the current best estimate of the U.S. regulatory framework for the 1980's and beyond.

The NOI format is illustrated in Figure 2-1, which is an excerpt from the third NOI. The frequency spectrum is divided into disjoint but contiguous intervals according to allocated service. For example, the band 20.2 - 21.2 GHz is allocated to satellite downlink service for fixed or mobile earth stations in government systems. The use of all capitals (i.e., "FIXED-SATELLITE") indicates primary allocation status; the use of leading capitals (i.e., "Standard Frequency and Time Signal-Satellite") indicates secondary allocation status. In conflicts among services at different allocation levels, the secondary service must give way to the primary service. Primary services may continue to interfere with secondary services, but not vice versa. Where they exist, parenthetical expressions represent limitations on a particular service. For example, all services in Figure 2-1 are limited to space-to-earth links. Other bands would be needed to support earth-to-space uplinks or space-to-space crosslinks. Footnotes add additional limitations and refinements to the allocation table. In Figure 2-1, the U.S. Government footnote GYY4 limits the illustrated band to military operations.

Since TDAS is envisioned primarily as a service of the U.S. government, the Table of Government Allocations was examined for applicable service authorizations. Non-government use is not precluded by this approach since coordination through NASA would be allowed. Allocations applicable to TDAS service are listed in Table 2-2, where a dichotomy is introduced to identify service classifications by link type or end-use. Inter-satellite service applies to any satellite-to-satellite service, regardless of data type and spacecraft identity. Fixed-satellite service similarly applies to any up/downlink between a satellite and ground station. Services classified by end use are nominally limited to particular user classes. In the absence

FIGURE 2-1: SAMPLE FORMAT OF FCC NOTICE OF INQUIRY

(PROPOSED)

INTERNATIONAL TABLE			UNITED STATES TABLE		FCC USE DESIGNATORS	
			GOVERNMENT	NON-GOVERNMENT		
Region 1 Allocation GHz (1)	Region 2 Allocation GHz (2)	Region 3 Allocation GHz (3)	Allocation GHz (4)	Allocation GHz (5)	RULE PART(s) (6)	Special-Use Frequencies (7)
19.7 - 20.2	FIXED SATELLITE (space-to-Earth) Mobile-Satellite (space-to-Earth) 3800M		19.7 - 20.2	19.7 - 20.2 FIXED-SATELLITE (space-to-Earth) Mobile-Satellite (space-to-Earth)		
20.2 - 21.2	FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) Standard Frequency and Time Signal Satellite (space-to-Earth) 3800M		20.2 - 21.2 FIXED-SATELLITE (space-to-Earth) MOBILE-SATELLITE (space-to-Earth) Standard Frequency and Time Signal-Satellite (space-to Earth) GYY4	20.2 - 21.2 Standard Frequency and Time Signal-Satellite (space-to-Earth)		

GYY4 In the bands 7250-7750 and 7900-8400 MHz and 20.2-21.2, 30-31, 39.5-40.5, 43.5-45.5 and 50.4-51.4 GHz the fixed-satellite and mobile-satellite services are limited to military operations.

TABLE 2-2
SERVICE CLASSIFICATIONS APPLICABLE TO TDAS

Services Classified by Link Type	Services Classified by End-Use*
Intersatellite	Space Operations
Fixed-Satellite*	Space Research
	Meteorological-Satellite
	Earth Exploration-Satellite

* Limitations may apply, indicated in the Table of Frequency Allocations by a parenthetical expression. For example, Meteorological-Satellite (space-to-earth) would limit the indicated band to downlinks from meteorological satellites.

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of specific coordinating agreements by all interested parties, for example, the space telescope would be precluded from a band allocated solely to the meteorological-satellite service. Such end use classifications are difficult to incorporate in a TDAS intended for broad user support. Bands allocated in this way are, nevertheless, retained at this stage to provide maximum flexibility for future tradeoffs.

The strategy employed was to examine all frequency bands in the proposed U.S. Table of Government Allocations and extract those bands applicable to TDAS. Table 2-3 lists all bands applicable to the inter-satellite service, including bands classified by enduse that support space-to-space service. Table 2-4 lists all bands applicable to the fixed-satellite service (uplinks and downlinks to fixed earth stations), including bands classified by enduse that support uplink/downlink service. For each band of interest, the allocation(s) in support of TDAS-type activity is indicated in column 2 -- "Allocated Services Relevant to TDAS." Other service allocations for government and non-government users are listed in column 3. This allows comparison of TDAS allocation status to the allocation status of all other services. Comments are added where required to describe related data and footnotes that may modify the sense of allocation.

Tables 2-3 and 2-4 indicate extensive support in the proposed regulatory framework for TDAS and TDAS-like service. However, certain discrepancies may be noted among TDRSS frequency bands, ongoing research in space communications and the proposed regulations.

With respect to TDRSS frequency bands, comparison of Table 2-1 and Tables 2-3 and 2-4 indicate little support for TDRSS in the proposed allocations. Forward links (TDRSS-to-User) at S-band are not authorized in any way. All other services are authorized on a secondary basis and only for "space research". TDRSS services are only protected from interference by ongoing participation of NASA frequency managers.

TABLE 2-3

INTER-SATELLITE BANDS

Band (GHz)	Allocated Services relevent to TDAS	Other Allocated Services	Comments
2.2 - 2.29	SPACE RESEARCH (space-to-earth) (space-to-space)	FIXED MOBILE	Footnote G101 allows space operations*(space-to-earth) and EES (Space-to-earth) and (space-to-space) on a coequal basis TDRSS MA at center frequency of 2287.5 MHz Extensive RFI (military) Non-government services not allocated proposed regulations reduce upper end of band to 2.29 from 2.3 GHz due to radioastronomy from 2.29 - 2.3 GHz
13.4 - 14.0	Space Research	RADIOLOCATION Standard Frequency and Time Signal Satellite (Earth-to-Space)	Not all data services authorized Secondary allocation only

TABLE 2-3

INTER-SATELLITE BANDS (CONT)

Bands (GHz)	Allocated Services relevant to TDAS	Other Allocated Services	Comments
14.0 - 14.2	Space Research	FIXED-SATELLITE (Earth-to-space) RADIONAVIGATION	Not all data services authorized Secondary allocation only
14.5 - 14.7145	Space Research	FIXED Mobile	Not all data services authorized Secondary allocation only
14.7145 - 15.1365	Space Research	MOBILE Fixed	Not all data services authorized Secondary allocation only
15.1365 - 15.35	Space Research	FIXED Mobile	Not all data services authorized Secondary allocation only Passive sensing in this band Radio astronomy in upper adjacent band
23 - 23.55	INTER-SATELLITE	FIXED MOBILE	Radio astronomy spectral line observations at 23.07 - 23.12 GHz (footnote 3801 D)
25.25 - 27	Earth Exploration-Satellite (space-to-space)	FIXED MOBILE Standard Frequency and time Satellite (Earth-to-space)	

* See Glossary for Definition of these terms

TABLE 2-3

INTER-SATELLITE BANDS (CONT)

Band (GHz)	Allocated Services relevent to TDAS	Other Allocated Services	Comments
27 - 27.5	Earth Exploration-Satellite (space-to-space)	FIXED MOBILE	
54.25 - 58.2	INTER-SATELLITE	EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive)	EES* and IS services not protected against FIXED and MOBILE services Federal Republic of Germany, Japan, and UK allocate this band to radiolocation on a primary basis
59 - 64	INTER-SATELLITE	FIXED MOBILE RADIOLOCATION	Oxygen absorption band Industrial, scientific and medical service in 61 - 61.5 GHz, with special administration authorization
116 - 126	INTER-SATELLITE	EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive)	ISM* operations may be authorized in 122 - 123 GHz Radio astronomy in lower adjacent band SETI* in 120 - 126 GHz
126 - 134	INTER-SATELLITE	FIXED MOBILE RADIOLOCATION	
170 - 174.5	INTER-SATELLITE	FIXED MOBILE	174.42 - 175.02 GHz allocated to Radio astronomy on a secondary basis

TABLE 2-3

INTER-SATELLITE BANDS (CONT)

Band (GHz)	Allocated Services relevent to TDAS	Other Allocated Services	Comments
174.5 - 176.5	INTER-SATELLITE SPACE RESEARCH	EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE	174.42 - 175.02 GHz allocated to Radio astronomy on a secondary basis
176.5 - 182	INTER-SATELLITE	FIXED MOBILE	Secondary allocations to Radio astronomy in 177 - 177.4, 178.2 - 178.6 and 181 - 181.46 GHz Radio astronomy in upper adjacent band
185 - 190	INTER-SATELLITE	FIXED MOBILE	186.2 - 186.6 GHz allocated to Radio astronomy on a secondary basis Radio astronomy in lower adjacent band
300 - 400	NOT ALLOCATED	NOT ALLOCATED	

TABLE 2-4

FIXED-SATELLITE BANDS

Band (GHz)	Allocated Services Relevent to TDAS	Other Allocated Services	Comments
0.137 - 0.138	SPACE OPERATION (space-to-earth) METEOROLOGICAL-SATELLITE (space-to-earth) SPACE RESEARCH (space-to-earth)	NONE	
0.40015 - 0.401	METEOROLOGICAL SATELLITE SPACE RESEARCH (space-to-earth) SPACE OPERATION (space-to-earth)	METEOROLOGICAL AIDS (radiosonde)	
0.401 - 0.402	SPACE OPERATION (space-to-earth) Earth Exploration-Satellite (earth-to-space) Meteorological Satellite (earth-to-space)	METEOROLOGICAL AIDS (radiosonde)	
0.402 - 0.403	Earth Exploration-Satellite (earth-to-space) Meteorological-Satellite (earth-to-space)	METEOROLOGICAL AIDS (radiosonde)	

TABLE 2-4

FIXED-SATELLITE BANDS (CONT)

Band (GHz)	Allocated Services Relevent to TDAS	Other Allocated Services	Comments
0.460 - 0.470	Meteorological-Satellite (space-to-earth)	LAND MOBILE	U.S. FOOTNOTE 201: In the band 460 - 470 MHz, space stations in the earth exploration satellite service may be authorized for space-to-earth transmissions on a secondary basis with respect to the fixed and mobile services. When operating in the meteorological-satellite service, such stations shall be protected from harmful interference from other applications of the earth exploration-satellite service. The power flux in this band shall not exceed -152 dBw/m**2/4kHz. As specified in U.S. Footnote 216, the frequency bands 460.5125 - 460.5625, 462.9875 - 463.1875, 465.5125 - 465.5625 and 467.9875 - 468.1875 MHz are authorized for Government/non-Government operations in medical radio communications systems.

TABLE 2-4

FIXED-SATELLITE BANDS (CONT)

Band(GHz)	Allocated Services Relevent to TDAS	Other Allocated Services	Comments
1.427 - 1.429	SPACE OPERATION (Earth-to-space)	FIXED MOBILE except aeronautical mobile Fixed (telemetering) Land Mobile (telemetering and telecommand)	Radio astronomy in lower adjacent band SETI by some countries
1.990 - 2.110	[See Comments]	FIXED MOBILE	Footnotes listed below allow Earth-to-space and space-to-space operations for space research and Earth exploration service, with some restrictions and on a case-by-case basis. Relevent Footnotes: U.S. 90 U.S. 111 Current utilization by government earth stations in the band 2035 - 2110 MHz
2.2 - 2.29	SPACE RESEARCH (space-to-Earth) (space-to-space)	FIXED MOBILE	Footnote G101 allows space operations (space-to-earth) on a coequal basis TDRSS MA at center frequency of 2287.5 MHz Extensive RFI (military)

TABLE 2-4

FIXED-SATELLITE BANDS (CONT)

Band (GHz)	Allocated Services Relevent to TDAS	Other Allocated Services	Comments
7.19 - 7.235	SPACE RESEARCH (Earth-to-space)	FIXED	Passive microwave sensing performed in this band
7.25 - 7.30	FIXED-SATELLITE (space-to-Earth)	MOBILE-SATELLITE (space-to-Earth) Fixed	Government use is limited to military operations by footnote GYY4
8.025 - 8.175	EARTH EXPLORATION-SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space)	FIXED Mobile-Satellite (no airborne transmissions)	Non-government allocation is primary for EES. Authorizations on a case-by-case basis for EES. Fixed-satellite service limited to military
8.175 - 8.215	EARTH EXPLORATION SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space) METEOROLOGICAL-SATELLITE (Earth-to-space)	FIXED Mobile-Satellite (Earth-to-space) (no airborne transmissions)	Non-government allocation is primary for EES. Authorizations on a case-by-case basis for EES. Fixed-satellite service limited to military

TABLE 2-4

FIXED SATELLITE BANDS (CONT)

Band (GHz)	Allocated Services Relevent to TDAS	Other Allocated Services	Comments
8.215 - 8.4	EARTH EXPLORATION SATELLITE (space-to-Earth) FIXED-SATELLITE (Earth-to-space) (no airborne transmissions)	FIXED Mobile Satellite (Earth-to-space) (no airborne transmissions)	Non-government allocation is primary for EES. Authorizations on a case-by-case basis for EES. Fixed-satellite service limited to military
8.45 - 8.5	SPACE RESEARCH (space-to-earth)	FIXED	
13.25 - 13.4	Space Research (Earth-to-space)	AERONAUTICAL-RADIONAVIGATION	
13.4 - 14.0	Space Research	RADIOLOCATION Standard Frequency and Time Signal Satellite (Earth-to-space)	
14.0 - 14.2	Space Research	RADIONAVIGATION FIXED SATELLITE (Earth-to-space) (nongovernment)	

TABLE 2-4

FIXED SATELLITE BANDS (CONT)

Band (GHz)	Allocated Services relevent to TDAS	Other Allocated Services	Comments
14.5 - 14.7145	Space Research	FIXED Mobile	
14.7145 - 15.1365	Space Research	MOBILE Fixed	
15.1365 - 15.35	Space Research	FIXED Mobile	
20.2 - 21.2	FIXED-SATELLITE (space-to-Earth)	MOBILE-SATELLITE (space-to-Earth) Standard Frequency and Time Signal-Satellite (space-to-Earth)	Limited to military operations by footnote GYY4
30.0 - 31.0	FIXED-SATELLITE (Earth-to-space)	MOBILE-SATELLITE (Earth-to-space) Standard Frequency and Time Signal-Satellite (space-to-Earth)	Limited to military operations by footnote GYY4

TABLE 2-4

FIXED SATELLITE BANDS (CONT)

Band (GHz)	Allocated Services relevent to TDAS	Other Allocated Services	Comments
39.5 - 40.5	FIXED-SATELLITE (space-to-Earth)	MOBILE-SATELLITE (space-to-Earth)	Limited to military operations by footnote GYY4
42.5 - 43.5	FIXED-SATELLITE (Earth-to-space)	FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY	Inband radio astronomy activities require coordination
47.2 - 50.2	FIXED-SATELLITE (Earth-to-space)	FIXED MOBILE	Radio astronomy spectral line observations in 48.94 - 49.04 GHz
65 - 66	EARTH EXPLORATION-SATELLITE SPACE RESEARCH	Fixed Mobile	
71 - 74	FIXED-SATELLITE (Earth-to-space)	MOBILE MOBILE-SATELLITE (Earth-to-space) MOBILE	72.77 - 72.91 is also allocated to radio astronomy
74 - 75.5	FIXED-SATELLITE (Earth-to-space)	FIXED MOBILE	
81 - 84	FIXED-SATELLITE (space-to-Earth)	FIXED MOBILE MOBILE-SATELLITE (space-to-Earth)	

TABLE 2-4

FIXED SATELLITE BANDS (CONT)

Band (GHz)	Allocated Services Relevent to TDAS	Other Allocated Services	Comments
92 - 95	FIXED-SATELLITE (Earth-to-space)	FIXED MOBILE RADIOLOCATION	93.07 - 93.27 is also used for radio astronomy spectral line measurements
102 - 105	FIXED-SATELLITE (space-to-Earth)	FIXED MOBILE	SETI over entire band Radio astronomy in upper adjacent band
149 - 150	FIXED-SATELLITE (space-to-Earth)	FIXED MOBILE	
150 - 151	FIXED-SATELLITE (space-to-Earth)	EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive)	
151 - 164	FIXED-SATELLITE (space-to-Earth)	FIXED MOBILE	Radio astronomy in upper adjacent band
202 - 217	FIXED-SATELLITE (Earth-to-space)	FIXED MOBILE	SETI over entire band
231 - 235	FIXED-SATELLITE (space-to-Earth)	FIXED MOBILE Radiolocation	Radio astronomy in lower adjacent band
235 - 238	FIXED-SATELLITE (space-to-Earth)	EARTH EXPLORATION-SATELLITE (passive) FIXED MOBILE SPACE RESEARCH (passive	

TABLE 2-4

FIXED SATELLITE BANDS (CONT)

Band (GHz)	Allocated Services Relevent to TDAS	Other Allocated Services	Comments
238 - 241	FIXED-SATELLITE	FIXED MOBILE Radiolocation	
265 - 275	FIXED-SATELLITE (Earth-to-space)	FIXED MOBILE RADIO ASTRONOMY	Radio Astronomy spectral line observation in the following bands: 265.64 - 266.16 267.34 - 267.86 271.74 - 272.26
300 - 400	NOT ALLOCATED	NOT ALLOCATED	

With respect to ongoing research in space communications, the currently active 30/20 GHz research program (NASA's Advanced Communications Technology Satellite) must be viewed in the light of U.S. government footnote GYY4. This footnote limits government use of the bands 20.2 - 21.2 GHz, 30.0 - 31.0 GHz and 39.5 - 40.5 GHz to military applications.* With the exception of these bands, limited to military applications, the spectrum from 16 GHz to 40 GHz is devoid of government allocations for earth-space links. This would seem to preclude a desirable frequency band for TDAS usage. On the other hand, coordination with military authorities may be mutually desirable in view of the likely dual military/civilian support afforded by a TDAS. Since the footnote applies strictly to the U.S. Table of Frequency Allocations (i.e., no international ramifications), coordination is only necessary within the United States.** Due to the technical desirability of 30/20 GHz, an effort should be made to secure waiver of footnote GYY4 with respect to TDAS, and coordinate use of this band with the military. A case promoting coordinated use of 30/20 GHz could be found along the following lines:

a) <u>Advantage of dual use</u>. If TDAS is allowed to operate at 30/20 GHz, military users of TDAS derive the benifits available at those frequencies. If TDAS waiver of the footnote is <u>not</u> secured, two options are possible. TDAS could operate entirely at other frequency bands, or TDAS could support dual military and nonmilitary communication packages — with the military package operating at 30/20 GHz. The first option represents inferior performance for all users due to the technical disadvantages of other bands. The second option represents a weight, power, and cost penalty required to support dual payloads.

* The 39.5 - 40.5 GHz band is allocated to Fixed-Satellite service for non-government users. In addition, bands <u>adjacent</u> to the 20.2 - 21.2 GHz and 30.0 - 31.0 GHz bands support Fixed-Satellite service for non-government users. However, the activity and interest in these bands may make it difficult to authorize TDAS services in these non-government bands, should the current proposed regulations be implemented

** The coordination procedure required to secure waiver or modification of a government footnote is typically a process of negotiating among the interested parties; this is in contrast to the relatively more protected effort required to coordinate government and non-government users, especially in cases where government use encroaches on non-government allocations.

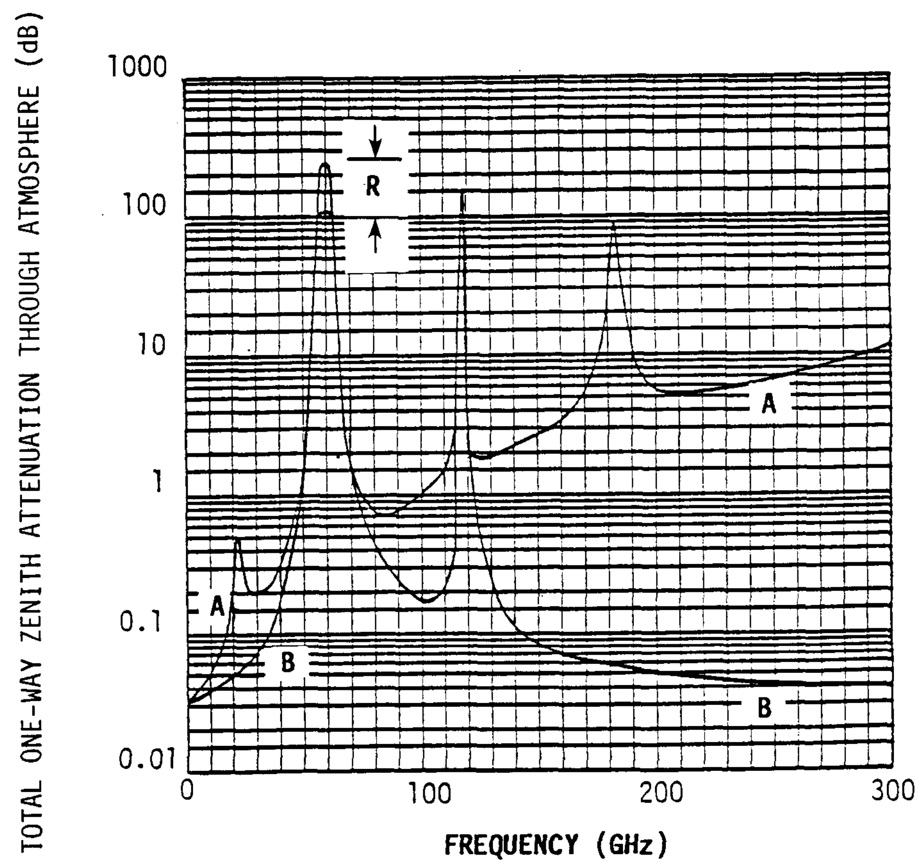
b) Negligible RFI impact of dual use. Since TDAS will employ a small number of large, fixed earth stations, there will be minimal impact of TDAS 30/20 GHz utilization on other users of the band. Coordination within CONUS, and the lack of TDAS earth-space links outside CONUS, imply minimal impact on worldwide military operations.

With respect to the entire spectrum, allocated bandwidths tend to increase along with band center frequency. Technology constraints as well as extensive competition in the commercially mature regions of the spectrum tend to decrease available bandwidths at the lower frequencies (the spectrum below $\approx$ 10 GHz is finely subdivided to support a wide range of government and non-government activities). From a planning perspective higher frequencies afford increased bandwidth and protection against RFI, but they also increase technical risk.

Atmospheric absorption follows a generally increasing trend as frequency increases and additionally exhibits several extreme regions of absorption due to molecular resonance of oxygen and water vapor. This characteristic is illustrated in Figure 2-2. In the millimeter-wave region of the spectrum (30 GHz - 300 GHz), inter-satellite allocations are typically close to the absorption maxima while fixed-satellite allocations are near the absorption minima. However, this is only generally true and attenuation should be checked for each specific frequency band candidate as part of the tradeoff process. For example, broad bands allocated to inter-satellite service between 54 GHz and 64 GHz actually straddle an absorption peak. While the absorption maximum is in excess of 100 dB, frequencies at either end of this band experience attenuations on the order of only 10 to 50 dB. This implies wide differences in the level of RFI protection afforded to inter-satellite links via atmospheric attenuation of terrestrial emissions, unless care is exercised in frequency selection within a broad allocated band.

Finally, the generally rising trend exhibited by Figure 2-2 implies a penalty for high-frequency up/downlinks. Under clear-sky conditions, low

FIGURE 2-2: TOTAL ONE-WAY ZENITH ATTENUATION THROUGH THE ATMOSPHERE AS A FUNCTION OF FREQUENCY. CURVE A, MODERATE HUMIDTY (7.5 g/m^3 AT SURFACE); CURVE B, DRY ATMOSPHERE (0 g/m^3). REGION R IS RANGE OF VALUES DUE TO FINE STRUCTURE. [13]



elevation angle links at 80 or 90 GHz would experience clear-sky attenuation of 1 dB to 3 dB. Attenuation due to rainfall is greater as well. Figures 2-3 and 2-4 illustrate rain attenuation* at four frequencies and two different operating scenarios, for the TDRSS spacecraft locations. These figures highlight the major points regarding rain attenuation. First, significant differences exist among potential ground terminal sites. Second, a heavy price must be paid to achieve 99.9% link availability, as apposed to 99%. Particularly at the 90/80 GHz frequencies, the margin required to achieve 99.9% availability substantially exceeds 10 dB. At the lower 30/20 GHz bands, additional margin to achieve 99.9% availability rarely exceeds 10 dB. Third, for a given availability and ground site location, the differential attenuation between 30/20 GHz and 90/80 Ghz is substantial. At a 99% availability level, most sites experience a differential attenuation on the order of 10 dB**. At the higher availability level of 99.9%, differential attenuations exceed 20 dB in all cases except Denver. Fourth, site diversity is generally <u>not</u> effective in combating fades at these availability levels. The underlying impairment at the 99% and 99.9% availability levels, is <u>stratiform</u> rain. Site diversity is chiefly geared toward fading due to thunderstorm events. The link availability is a function of user needs and system requirements, but it is clear that rain can exact a heavy penalty at 80 GHz.

It appears that millimeter-wave alternatives exist to the 30/20 GHz bands, although these alternatives involve increased technical risk and higher cost. Further research can refine the tradeoffs involved, but the 30/20 Ghz band is currently the primary technical choice for up/down access. Use of 30/20 Ghz is contingent on securing waiver of government footnote GYY4.

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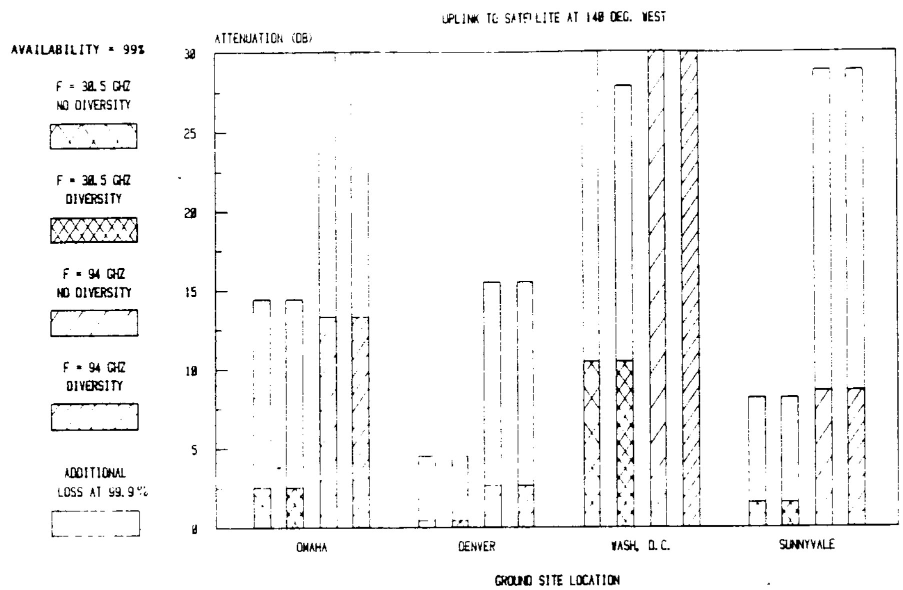
* Analysis of rain attenuation was based on the Crane model as reported in [13].

** The major exception is Denver, which has relatively low margin requirements due to its high elevation and the corresponding short communication path through the rain layer.

FIGURE 2-3: RAIN ATTENUATION ON EARTH-SPACE LINKS



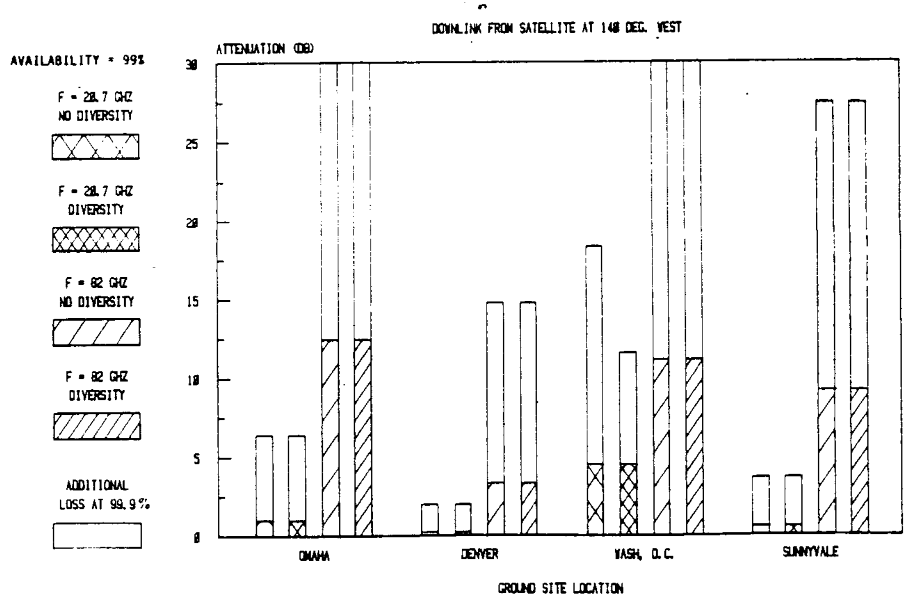


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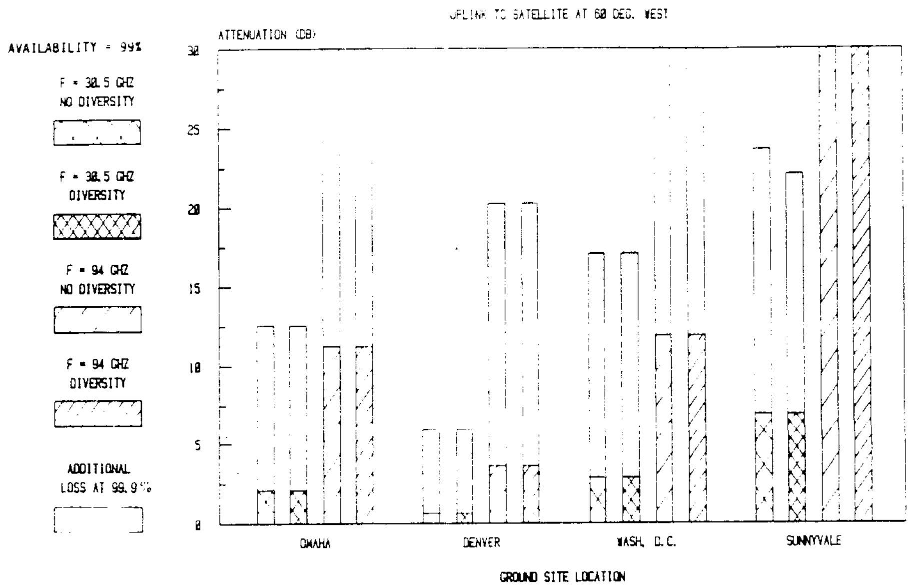
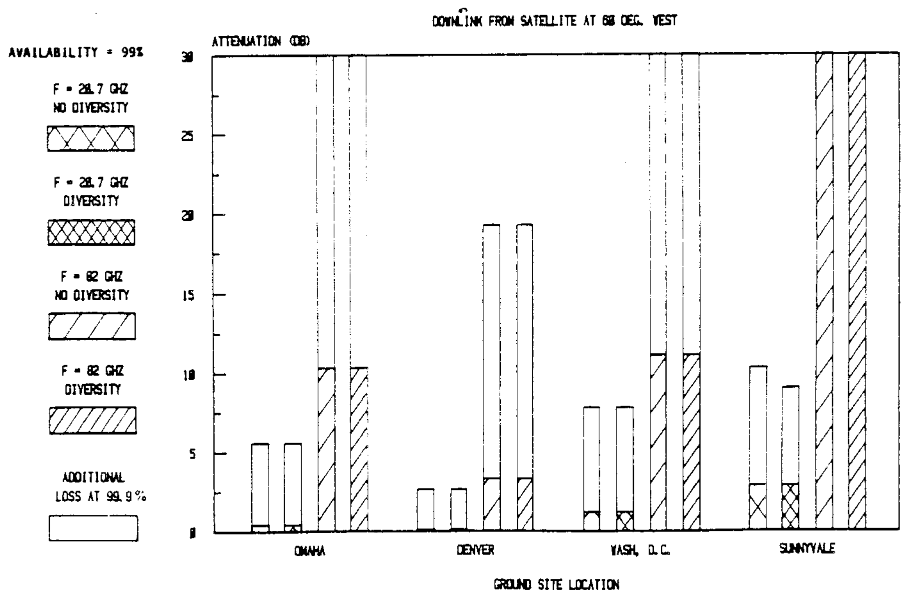
FIGURE 2-4: RAIN ATTENUATION ON EARTH-SPACE LINKS





2.3 LASER-BASED TECHNOLOGIES

The use of optical wavelengths* for TDAS is constrained by technical and physical factors rather than regulatory constraints.

Technically, selection of a laser communications system for TDAS in the 1990's is limited to three wavelength regions:

1. 0.832 μm supported by GaAs laser technology
2. 1.06 μm supported by ND:YAG laser technology
3. 0.532 μm supported by frequency-doubled ND:YAG laser technology

GaAs is a primary candidate for TDAS-to-TDAS crosslinks. ND:YAG is an alternative (to GaAs) for user-to-TDAS ultra-high data rate laser single access service.

The laser technologies involved are approaching the point of operational feasibility in terms of power output, date rate, lifetime and space qualifications. However, neither GaAs nor ND:YAG communication systems have been fully qualified in terms of reliability and lifetime at the time of this writing [7]. The technical issues and tradeoffs relating to these technologies are outside the scope of this report; further information is available in [6], [8], [9] and [14] for blue-green and infrared communication systems.

Physically, laser communication on earth-space links is severely restricted by weather conditions. While research continues in satellite-to-submarine laser communication in the blue-green region [8], [9], the goal is a very low data rate system not easily adapted to TDAS. In an operational system such as TDAS, requiring high data rates and high link reliability with a cost effective system, laser communication appears unsuited to earth-space links.

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* Optical bands are typically specified by wavelengths rather than frequency. Blue-green light at 523 nm (1 nm = 1 nanometer = 10^{-9} meter) corresponds to a frequency of $\approx$ 5.7 x 10^{14} Hz, or 570,000 GHz.

Space-space links provide an application for laser technology with one or several of the technologies noted above. Unlike earth-space links, exoatomospheric laser communication is essentially free of molecular absorption, scattering and dispersion. This offers a natural medium for the highly collimated wide bandwidth signals possible with laser equipment.

Currently, there are no regulations that limit the use of laser communication systems. Selection of a laser alternative (or alternatives) should be based on technical characteristics and risk.

SECTION 3

PROJECTED SURVIVABILITY TO RADIO FREQUENCY INTERFERENCE

This section develops a model of RFI incident on TDAS, and projects TDAS survivability. Four generic sources of RFI can be identified:

1. Natural Sources. The sun emits electromagnetic radiation at all frequencies of interest to TDAS, and is therefore an important source of RFI for selected geometries.

2. Self-interference. In system configurations where several user satellites (USATs) share a common operating frequency, self-interference could lead to unacceptable degradation of user signaling.

3. Other civilian services. Many frequency bands that are physically appropriate for TDAS are allocated jointly to several radio services. In cases where a non-TDAS service is granted higher allocation status relative to TDAS, degradation of TDAS signaling could take place without a regulatory remedy.

4. Military services. Certain strategic and tactical radars generate high-power unintentional RFI. Such RFI will degrade the frequency bands chosen for TDRSS, and can be expected to become more severe in the future.

TDAS survivability to these RFI sources depends on the system architecture, frequency plan, spacecraft design, user mission profiles and time of year (particularly with respect to solar outages). In this study our discussion of TDAS survivability is limited to potential RFI sources. Man-made RFI emitters are assumed to fully utilize the RF spectrum consistent with proposed FCC/NTIA regulations (based on WARC '79 and the FCC Notices of Inquiry in response to the WARC).

This section is organized into four subsections relating to the four sources of RFI listed above. Each subsection describes RFI characteristics and potential interference modes relative to TDAS.

3.1 NATURAL SOURCES OF RFI

For practical purposes, the sun is the only natural source of RFI. While other natural sources of electromagnetic radiation exist (e.g., terrestrial blackbody radiation, cosmic background radiation, etc.), they are typically low-energy and well-behaved. As a result, their effects are absorbed in the baseline link budget in the form of anticipated thermal noise at the antenna. In contrast to these sources, the sun emits high-level electromagnetic radiation at all frequencies of interest to TDAS, and it is impractical to design receiver/transmit systems against worst-case solar noise. Other methods must be employed to mitigate solar RFI. This subsection identifies the scope of the solar RFI problem, and Section 4 addresses mitigating techniques that may be selected to combat it.

The geometries for solar RFI on space-to-space links are illustrated in Figure 3-1(a) and (b). The assumption here is that TDAS satellites are in nearly geostationary orbits.* Figure 3-1(a) illustrates the geometry at spring or autumn equinox. Solar radiation is parallel to the equatorial plane, and satellites in this plane may move into conjunction with the sun. In the absence of earth blockage effects, satellites in dual geosynchronous orbits would achieve solar conjunction twice per orbit during the period of equinox, with each satellite eclipsing the solar disk once with respect to the other satellite. With a geostationary TDAS and a USAT in low earth orbit, there are an additional two conjunctions each time the USAT "laps" the TDAS.

During any conjunction as described above, reliable transmission from the eclipsing satellite to the eclipsed satellite will be impossible. However, certain equipment designs may allow reliable communication in the other direction (where the eclipsing satellite positions the incident solar

* If TDAS utilizes slight eccentricity or inclination to enhance physical survivability, the effects noted in this section would be modified somewhat, but would remain <u>qualitatively</u> unchanged.

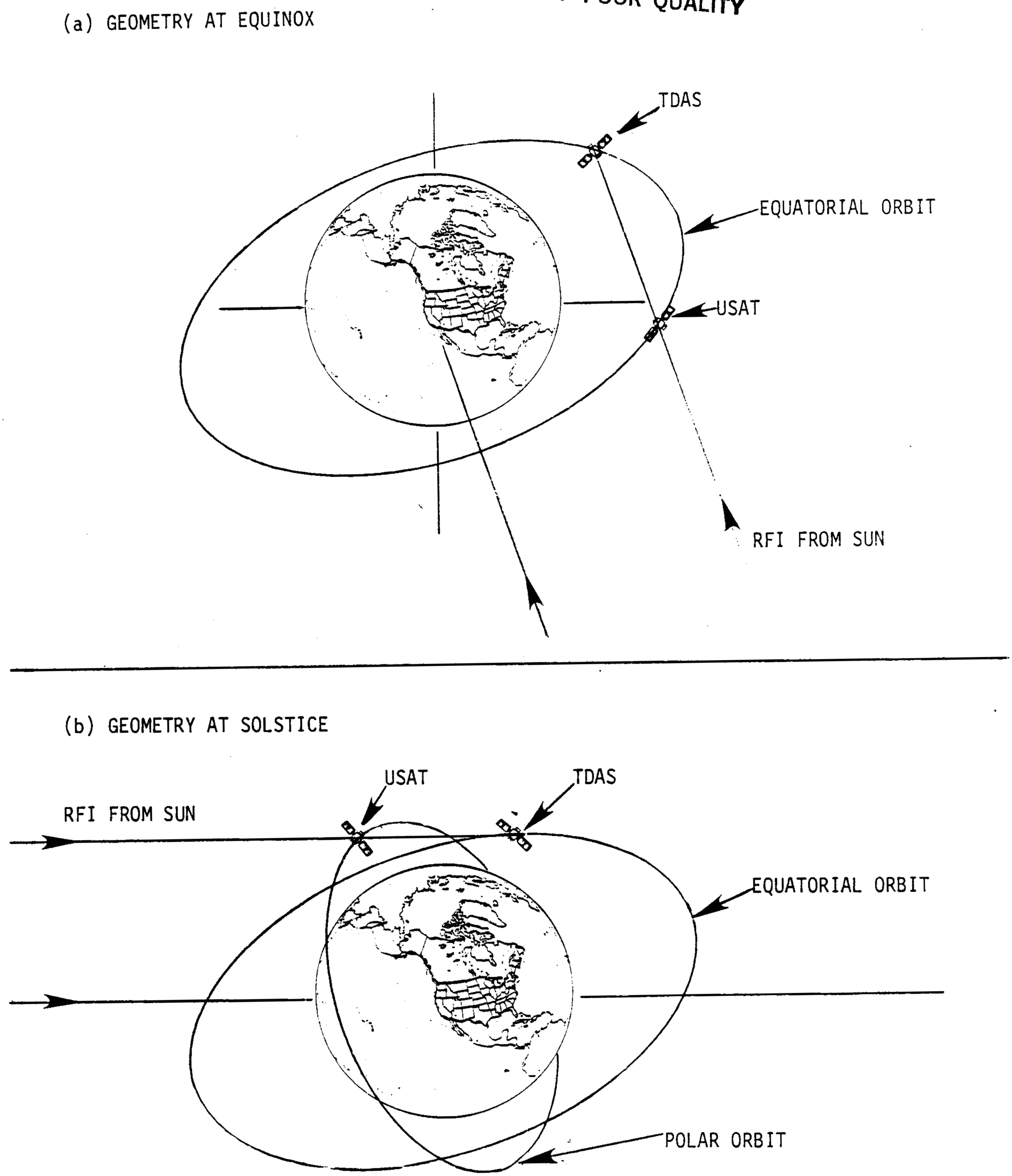

FIGURE 3-1: TDAS GEOMETRIES FOR SOLAR RFI

radiation in its receiving antenna's backlobe). The utility of such simplex communication depends on overall system architecture and operating requirements.

The duration of outage at conjunction can be calculated from orbital geometries, available link margins and spacecraft antenna designs. The solar disk subtends of angle of .48° from the vicinity of the earth [12], which is narrower than traditional spaceborne antenna beamwidths but may be on the order of beamwidths in the TDAS era.* The sun is perceived as a disk of extreme thermal noise with a minimum noise temperature for a mean quiet sun of 25,000°K for a single polarization [Hogg, 1968, reported in [12]]. To a first approximation, conjunction extends over the period in which at least part of the sun is within the main beam of the receiving spacecraft's antenna. For dual geosynchronous satellites, this is

$$\text{Conjunction Duration} \cong \left[\frac{\text{max (antenna beamwidth, solar dia.)}}{360^\circ}\right] (24 \text{ hours})$$

$$\cong \left[\frac{\text{max (antenna beamwidth, } 0.48^\circ)}{360^\circ}\right] (24 \text{ hours})$$

where duration is in hours and beamwidth is in degrees. The period of communication outage will typically extend beyond the period of conjunction, since antenna gain does not drop to zero outside the nominal beamwidth. The additional extent can be calculated with knowledge of specific equipments, link budgets and performance requirements.

The period of time immediately before and after an equinox is susceptable to conjunction in direct proportion to the parameters affecting outage duration (i.e., receive antenna beamwidth, equipment capabilities, link budgets and performance requirements). Conjunctions will occur while the sun is within one beamwidth of the celestial equator. Outages will extend over a greater time window, dependent on exact system architecture and requirements.

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* Laser receivers represent a notable example.

Figure 3-1(b) illustrates an outage geometry for a non-equatorial USAT (here depicted in a near-polar orbit). The Earth-Sun geometry is that of a summer solstice. Due to the USAT's highly inclined orbit, conjunction is possible at any time of year. Vulnerability throughout the year exists for any satellite whose inclination equals or exceeds ≈23.5°, the angle between earth's axis and the plane of the ecliptic. With non-equatorial USAT's, conjunctions may fail to occur on a twice per-orbit basis. The added dimension of motion outside the equatorial plane introduces variability in the occurance of conjunctions.

The preceeding discussion has concentrated on space-to-space link degradation. Space-to-earth downlinks from TDAS experience a similar problem around the equinoxes. The extent of this problem depends on ground station latitude, the difference in longitude between the earth station and the TDAS subsatellite point, and the beamwidth of the ground antenna. This outage occurs for approximately six days twice yearly at apparent noon at the satellite longitude. Lundgren [1970,1943-1972] has described diversity arrangements of phased and slightly inclined orbit satellites, which avoid simultaneous outages by using a pair of satellites. However, these diversity satellites require earth terminal antenna or feed switching and satellite handover to avoid the outage [12].

A major characteristic of solar conjunctions is their predictability. For any orbital configuration, system architecture and performance requirement, outages can be predicted with virtual certainty. This characteristic can be exploited by the system designer, as described in Section 4.

3.2 RFI DUE TO SELF-INTERFERENCE

In system architectures employing frequency reuse among various satellite pairs, self-interference must be examined carefully. Depending on scheduling software, system loading and antenna equipments, self-interference could become a dominating influence on system performance and throughput.

The self-interference problem is best introduced by example. Assume TDAS system architecture incorporates the following elements:

- 3 TDAS satellites in geostationary orbit

- 5 entry ports per TDAS, utilizing 1-meter antennas, at frequency $f_c \equiv 60$ GHz

- Full system utilization by user satellites (USATs) in low earth orbit (LEO) at altitude 1200 nmi

With these assumptions, each TDAS actively supports 5 USATs at frequency f_c.

Significant RFI can only occur if two or more USATs, supported by the same TDAS, happen to be within a few beamwidths of one another as seen from the TDAS. This is the condition for main beam-to-main beam coupling. The 1-meter antennas assumed for TDAS have a 3 dB beamwidth of 0.4^o at W-Band. A 4^o separation between USATs provides 20 dB of antenna discrimination (CCIR small pattern [10]). Taking this separation as an operational constraint, each USAT can be considered the center of a field-of-view "patch" that subtends a solid angle of approximately 15×10^{-3} steradians.

The LEO spherical shell with altitude 1200 nmi subtends a solid angle of 0.132 steradians from GEO, so each USAT's field-of-view patch covers $\approx$10% of the available field-of-view. So there are approximately 10 USAT patches over the LEO sphere. If USAT viewing angles from TDAS are distributed randomly over this sphere*, the probability of random mutual interference is the probably of two or more repeats in a series of 5 Bernoulli trails, with a population of 10.**

* This ignores the fact that USATs are likely to travel in one of several "standard" orbits, and furthermore appear to accumulate at the limbs of the sphere (where motion vectors are radial to TDAS).

** Phrased another way; If a TDAS is allowed to select 5 USATs, with each USAT randomly assigned to one of ten locations, what is the probability that two of the five (at least) will have the same location?

P[interference]

$\cong$ P[duplication in 5 draws with replacement from a population of 10]

= P[duplication in first two draws]
 + P[no duplication in first 2 draws] · P[duplication on 3^{rd} draw]
 + P[no duplication in first 3 draws] · P[duplication on 4^{th} draw]
 + P[no duplication in first 4 draws] · P[duplication on 5^{th} draw]

$$=\left(\frac{1}{n}\right)+\left(\frac{n-1}{n}\right)\left(\frac{2}{n}\right)+\left(\frac{n-2}{n}\right)\left(\frac{n-1}{n}\right)\left(\frac{3}{n}\right)+\left(\frac{n-3}{n}\right)\left(\frac{n-2}{n}\right)\left(\frac{n-1}{n}\right)\left(\frac{4}{n}\right)=0.70;\ n=10$$

The typical assumptions noted above, therefore, yield an interference probability of approximately 70%. This level of self-interference, which is only one factor tending to reduce availability, is unacceptable in an operational system. The conclusion is that self-interference should be addressed throughout the design process, where solutions can be incorporated in a cost-effective manner. Possible solutions, such as FDMA and scheduling flexibility, are discussed in Section 4.

As with solar conjunctions, self-interference is predictable based on USAT orbits and known equipment compliments. This knowledge may be used to avoid or mitigate the problem.

3.3 RFI DUE TO OTHER CIVILIAN SERVICES

A review of Tables 2-3 and 2-4 indicates multiple allocations for all frequency bands listed. For example, frequency bands allocated to Fixed-Satellite (space-to-earth) downlink operations may be simultaneously allocated to fixed and mobile terrestrial user services. This multiple allocation strategy allows cross-service interference among individually authorized and law-abiding users. Two qualitatively different problems exist with respect to: (1) interference on space-space links; and (2) interference on earth-space links.

3.3.1 Civilian RFI on Space-Space Links

The primary civilian threat to TDAS space-space links are the fixed and mobile services. The fixed service includes point-to-point microwave and other radio transmissions among fixed, specified earth stations (but excludes broadcasting). The mobile service includes transmission among mobile and fixed land stations, as well as jointly mobile stations.* The fixed and nonmobile stations in these services represent potentially high-level sources of RFI, depending on geometry with respect to TDAS and possible attenuation due to atmospheric absorption.

Due to the variable geometry of TDAS space-space links, virtually all terrestrial stations are potential sources of background RFI; as a USAT transits the earth as viewed by a TDAS, the TDAS receive antenna beam examines a strip of territory "behind" the USAT. Geometry is illustrated in Figure 3-2. Note that the strip examined by TDAS's receive antenna beam is not necessarily the USAT's ground track.

Terrestrial stations with high-gain antennas are typically used for point-to-point transmission, and the antenna beam is unscanned.** In principle, many of these fixed stations could be excluded as potential sources of RFI due to orientation of transmissions away from TDAS locations (for example, stations transmitting northward from the continental United States). However, this situation must be viewed as serendipitous with respect to particular terrestrial stations. It becomes less likey as one considers stations near the earth's limb as viewed from TDAS.

High power stations operating in a broadcast mode, particularly fixed stations in the mobile service (i.e., ground stations for land-air or shore-ship transmission), represent a threat due to their near-isotropic transmissions.

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* Examples of these mobile service classes would be ship-shore and ship-to-ship respectively.

** This is in contrast to military stations, examined in Subsection 3.4, which typically scan over large solid angles.

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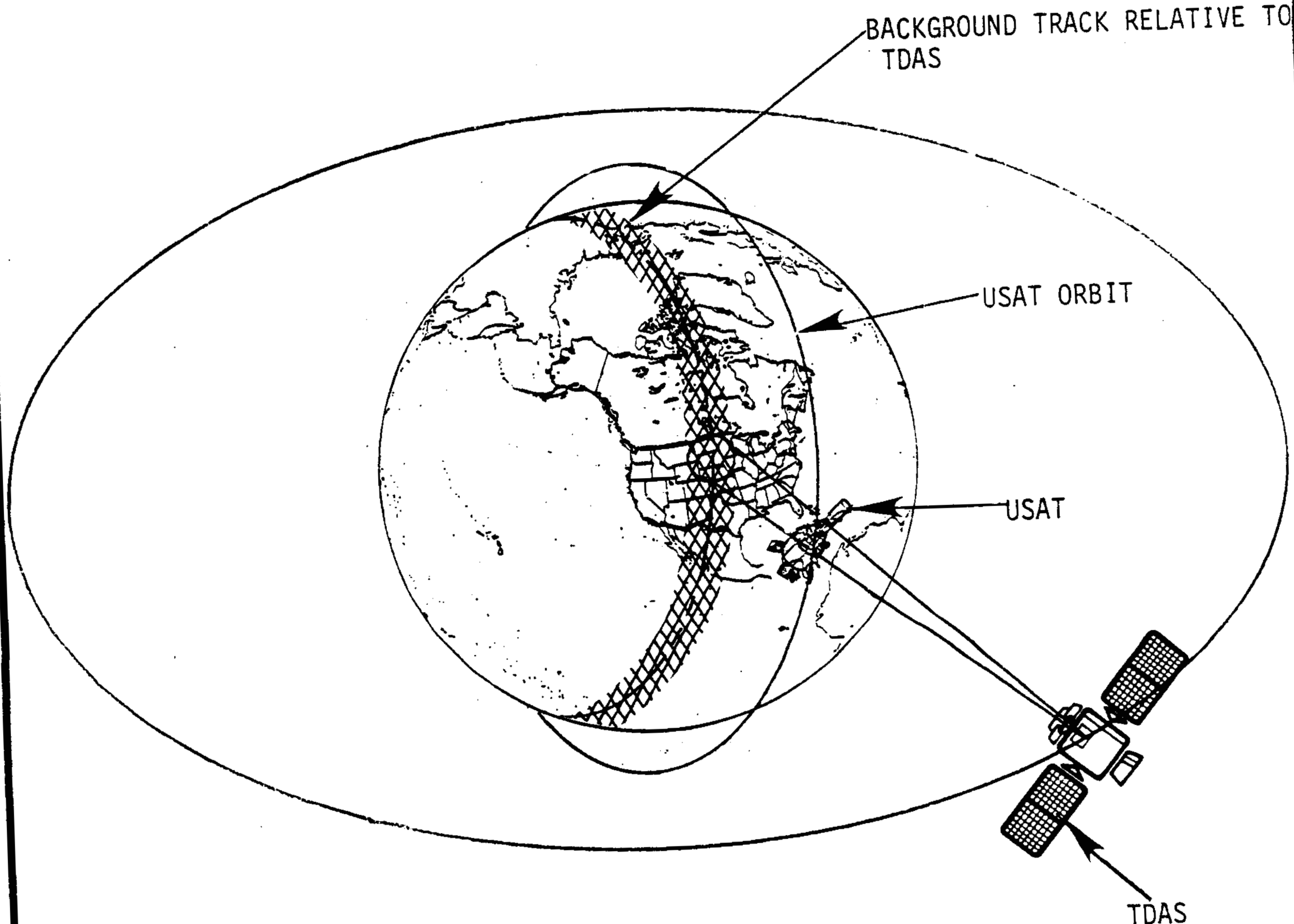
FIGURE 3-2: TERRESTRIAL RFI SOURCE GEOMETRY FOR TDAS



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Particularly in the case of low-gain USAT antennas, the inherent power advantage of ground-based transmitters over space-based transmitters indicates a potential source of RFI.

In addition to the fixed and mobile services discussed above, the 14.0 - 14.2 GHz band is allocated to non-government fixed-satellite earth-to-space transmissions. If this band is utilized by some non-government entity for communication with a nongeostationary satellite, interference could result when the non-government satellite and a TDAS satellite achieve conjunction with respect to the ground-based transmitter. Given the primary allocation status of the fixed satellite service and the secondary allocation status of TDAS activity in this band, such RFI would be unresolvable.

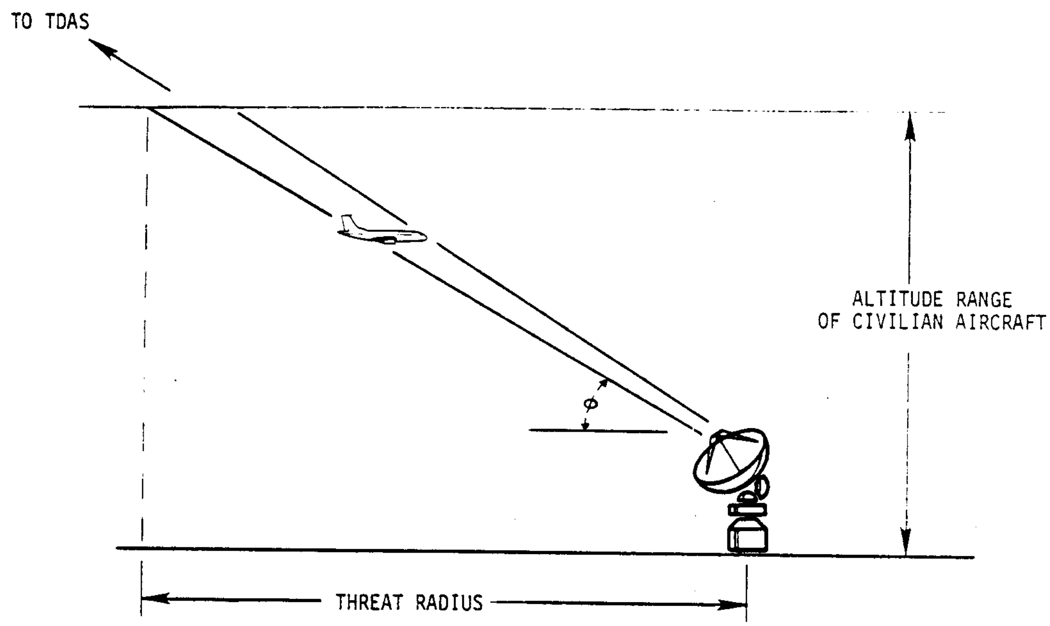
3.3.2 Civilian RFI on Earth-Space Links

TDAS Earth-space links are relatively secure against RFI since TDAS earth stations will employ high-power transmitters and high-gain antennas. High transmit EIRPs yield substantial protection against uplink RFI, while the high gain antenna provides discrimination for the downlink. The primary interference mode appears to be from air-mobile transmitters, which could conceivably inject RFI directly into the ground receiver's antenna beam. The geometry is illustrated in Figure 3-3. Due to the range advantage of the interfering aircraft, such RFI would have significant impact. Here again, the problem is unresolvable if the mobile service retains a superior allocation status relative to TDAS.

3.4 RFI DUE TO MILITARY SERVICES

Military services of the United States and foreign countries employ radar transmitters that pose a hazard to TDAS, albiet unintentional. These transmitters can be classified as either strategic or tactical, with unique RFI impact modes for each. This unclassified discussion summarizes RFI impact on TDRSS and identifies likely trends for the future. The material for

FIGURE 3-3: AIR-MOBILE RFI TO TDAS DOWNLINK



FOR: (1) ANTENNA ELEVATION ANGLE ϕ = 20°

(2) MAXIMUM AIRCRAFT ALTITUDE = 50,000 FEET

THEN: THREAT RADIUS = 26 STATUTE MILES

this discussion is based on an STI study, Ref.[11], "TDRSS RFI Impact Assessment".

Strategic radar impact on TDRSS is primarily at S-band, where Soviet air-defense radars generate pulsed RFI in TDRSS communication bands. This RFI affects forward and return link transmission between TDRSS and user satellites. The pulsed nature of this RFI makes it qualitatively different from nonmilitary RFI discussed above. In the frequency domain, this RFI extends over broad intervals in the forward and return link bands. The impact on TDRSS is sufficient to warrant a recommendation against use of SSA return and forward links, and MA forward links, in RFI zones over eastern Europe and east Asia. Whereas an unmodified TDRSS is vulnerable to such RFI, this is primarily due to a design optimized for benign environments. Planned modifications to TDRSS ground demodulation equipment will reduce the impact of RFI, and awareness of the problem can yield even greater mitigation in future systems.

Tactical radar impact on TDRSS is primarily at Ku-band, where currently sporadic RFI exists due to intermittant operation of tactical radars. Again, RFI is pulsed and exists over wide frequency intervals. Currently, K-band radar deployments are small and operating regimes are non-continuous. As with S-band RFI, forward and return link impact is due to a design optimized for a benign environment.

While the current impact of military RFI could be mitigated with careful design in a TDAS, the RFI environment is likely to become more severe in the future. This is due to the trend toward higher-power, higher-gain radar equipment and the simultaneous trend toward more continuous operating regimes (due to introduction of more reliable equipment). These trends indicate a need for careful examination of frequency bands considered for TDAS. RFI due to military radar equipment is a significant degrading influence, and must be examined on a band-by-band basis as the TDAS frequency utilization plan develops. For this assessment, care should be taken to project probable impact over the next two decades.

SECTION 4

TECHNIQUES FOR ROBUST OPERATION

This section describes nine techniques for improving TDAS link survivability and robustness in the presence of RFI. While none of these techniques is a panacea, various techniques in combination yield significant improvement against all types of RFI addressed in Section 3. The techniques discussed herein are:

- Frequency band selection to take advantage of atmospheric attenuation.
- Close coordination with other services, to achieve mutually desirable performance without sacrificing one service or another.
- Increased EIRP of satellite transmission equipment.
- Improved gain of satellite and ground antennas.
- Forward error correction (FEC) coding and interleaving of data and command messages.
- Regulatory injunction against identifiable interferers.
- Multiple routing through the multisatellite TDAS network.
- Signaling formats that provide modulation diversity in frequency, time or code.
- Command verification protocols that trap undetected errors in a primary transmission.

Table 4-1 tabulates these techniques against the four sources of RFI described in Section 3. The notations, indicating improvements in robustness (R) and survivability (S), should be viewed in a qualitative sense. A survivable system is typically able to operate in any anticipated RFI environment.* A robust system, on the other hand, provides some level of resistance and graceful degradation in the presence of harsh RFI environments without guaranteeing a specific level of performance.

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* We emphasize the word "anticipated".

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TABLE 4-1

TECHNIQUES FOR MITIGATING RFI

SOURCE OF RADIO FREQUENCY INTERFERENCE	MITIGATING TECHNIQUES								
	ATMOSPHERIC ATTENUATION	COORDINATION WITH OTHER SERVICES	INCREASED EIRP	IMPROVED GAIN	INTERLEAVING AND CODING	REGULATORY REMEDIES	MULTIPLE ROUTING	MODULATION DIVERSITY (FDMA, TDMA, CDMA)	COMMAND VERIFICATION PROTOCOLS
SOLAR			R	R	R		S		R
SELF INTERFERENCE				R	R		S	S	R
OTHER CIVILIAN SERVICES--IMPACT ON TDAS									
• SPACE-SPACE LINKS	S	R	R	R	R	R*	R		R
• EARTH-SPACE LINKS		R		R	R	R*			R
MILITARY SERVICES	S	R	R	R	S		R	R	R

R = IMPROVED ROBUSTNESS

S = IMPROVED SURVIVABILITY

* Regulatory remedies are a long-term solution to RFI problems discovered after start of operations. There is no guarantee of eventual success.

Each mitigating technique involves certain implementation costs. These must be borne by the user satellites, TDAS satellites, ground equipment and managerial infrastructure. The task of the system planner is to select some set of mitigating techniques that:

a) offers the required level of protection against the perceived RFI environment; and

b) shares the implementation costs equitably among all interested parties.

The second condition is particularly difficult to satisfy in a system with military, governmental, industrial and scientific user communities.

The remainder of this section addresses each mitigating technique in turn, with a brief description of capabilities and costs. The discussion is nontechnical, and intended primarily as an overview of available techniques.

4.1 FREQUENCY BAND SELECTION FOR ATMOSPHERIC ABSORPTION

A system design that takes advantage of atmospheric abosroption can enhance survivability of TDAS space-space links at relatively modest cost. The lowest frequency band offering significant attenuation is the 54-64 GHz band, with attenuations of 10 dB to over 100 dB. While the range of > 100 dB attenuation spans only ≈ 5 GHz, careful system design could share this bandwidth among the most vulnerable TDAS space-space links (i.e., USAT-TDAS and TDAS-USAT) and distribute the relatively less vulnerable links to the edges of the absorption region. The advantage of this technique is that terrestrial sources of RFI, military as well as civilian, become insignificant without excessive expenditure of power or coding complexity.

On the other hand, some development work would be required to exploit this band -- and atmospheric absorption is ineffective against solar RFI, self-interference and RFI experienced on Earth-space links.

4.2 COORDINATION WITH OTHER SERVICES

In most cases it is possible to alleviate RFI by negotiation and compromise with the entity responsible for the interference. An example is the air-mobile threat to the TDAS downlink, where a well-defined coordination area similar to that illustrated in Figure 4-1 could restrict non-TDAS use of particular frequencies. Such coordination becomes less practical as RFI impact regions become larger, since the operational effect on the interferer becomes more severe. This case may exist with multibeam downlinks.

The cost here is in the social sector, where additional administration is required and where non-TDAS activities may be degraded. The social and economic cost of such coordination must be assessed on a case-by-case basis.

4.3 INCREASED EIRP FOR SATELLITE TRANSMITTERS

Increasing the EIRP of TDAS and USAT transmitters is a brute-force method for achieving a measure of robustness. The excess EIRP translates directly into improved E_b/N_o at the receiver, or reduced J/S ratio if the RFI is due to interfering signals rather than thermal noise.* Against solar RFI, increased EIRP allows closer grazing angles with the sun before communication is lost. While actual conjunction still causes outage, the <u>period</u> of outage is reduced since EIRP can be traded for antenna offpointing discrimination. Against civilian and military RFI, increased EIRP reduces the <u>relative</u> strength of an interferer, yielding improved performance. Increased EIRP fails to address self-interference, since a user's increased power is offset by a proportionate increase by the interferer.** Increased EIRP is ineffective against the downlink threat posed by an air mobile interferer. Given the

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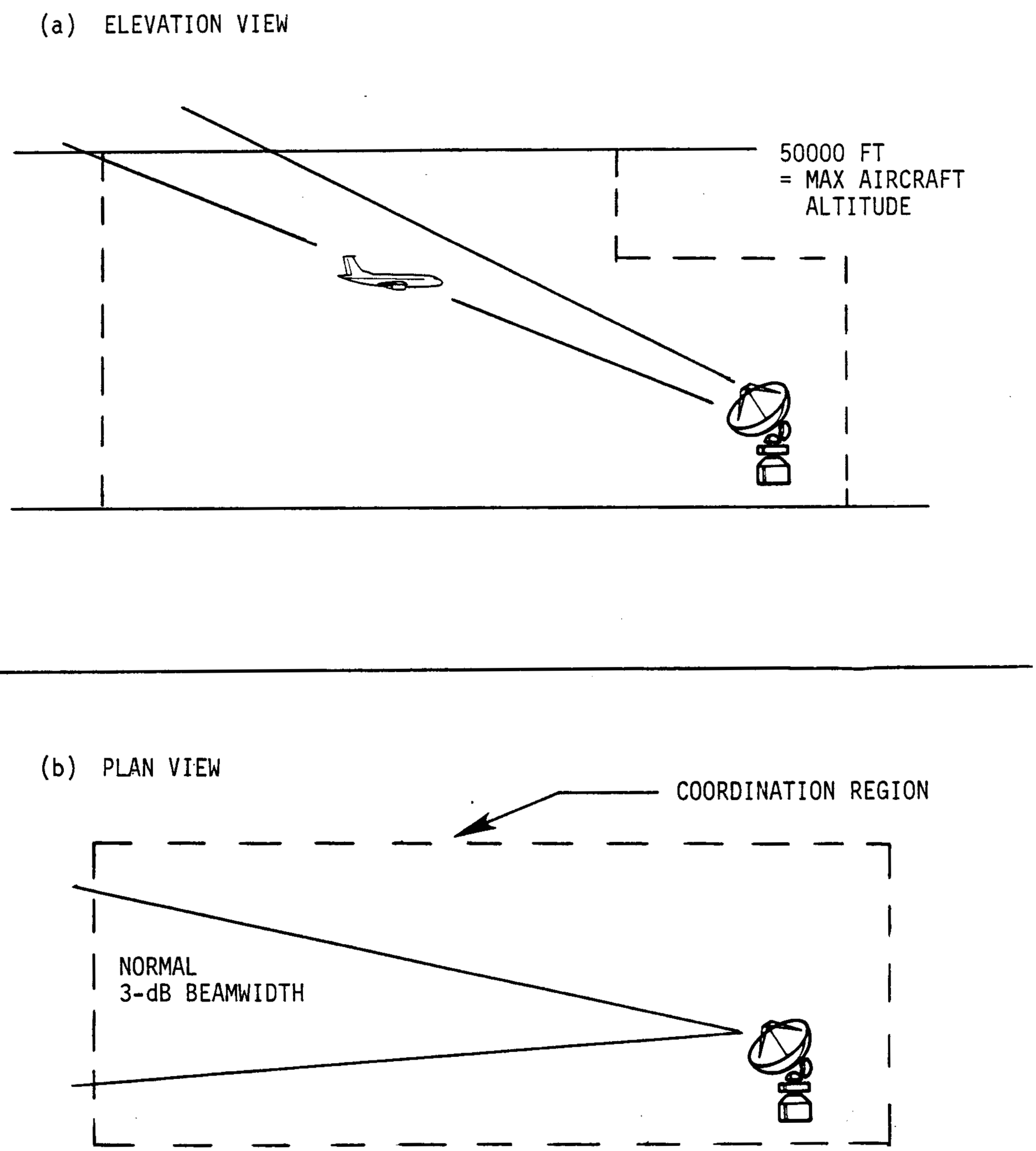
* The critical assumption with respect to reduced J/S ratio is that the interfering signal maintains constant power. This is true of signals from other services, civilian or military. It is false in the case of RFI due to self-interference.

** Disproportionate power increases within the TDAS community could protect certain users at the expense of others. This may be desirable for high-priority and manned missions.

FIGURE 4-1: COORDINATION REGION FOR TDAS DOWNLINK



range differential between a TDAS satellite and interfering aircraft, no reasonable increase in EIRP would overcome this problem.

The cost of increased EIRP is borne by the transmitting satellite(s). The increased power requirement translates into larger solar cell arrays and batteries, heavier support structures and electronics, and larger maneuvering fuel requirements.

4.4 IMPROVED GAIN FOR SATELLITE AND GROUND ANTENNAS

Improving the receive antenna gain yields a measure of robustness against all forms of RFI. The technique operates by narrowing the receive antenna beamwidth, thereby reducing the probability of main-beam-to-main-beam interference. In the case of solar RFI, outage time is reduced by improving the level of offpointing discrimination afforded by a given angular separation between transmit spacecraft and solar disk. In the case of downlink RFI from air mobile transmitters, improved ground antenna gain similarly narrows the antenna beamwidth and reduces the probability of aircraft occurrence in the beam. But while robustness is improved this technique does not achieve survivability since interference windows are only narrowed without being eliminated.

The cost of improved antenna gain is borne by the receiving spacecraft or ground station. In the case of spacecraft the additional weight involved in a larger antenna bears the additional penalty of heavier structures and larger maneuvering fuel requirements.

4.5 FORWARD ERROR CORRECTION CODING AND INTERLEAVING OF DATA AND COMMAND MESSAGES

Interleaving and FEC coding are discussed together since interleaving is ineffective without an underlying code to correct or detect errors.

Interleaving can be used in conjunction with a convolutional FEC code. Alternatively, a block code with burst-error correcting capability (such as a BCH code) can be used without an interleaver. The choice depends on the data rate, RFI scenario, correction ability required, and equipment constaints.

Since RFI due to military radar equipment is characterized by pulsed energy, interleaving and coding can enhance RFI survivability. The design issue is to characterize the periodicity and duration of RFI pulses. This data allows design of interleavers and codes optimized for the environment. The technique owes its effectiveness to the relatively short pulse durations of military radars.

RFI due to other civilian services, self-interference and solar conjunctions are more difficult to resolve by interleaving and coding alone. The problem here is the long duration of outages--on the order of seconds or minutes. For the high-end data rates expected in the TDAS era, interleaving spans to address these outage durations would be on the order of 10^8 or 10^{10} bits. This is far beyond the capability of present-day interleavers, and could introduce severe synchronization problems if ever implemented. It therefore appears that interleaving and coding fail to enhance survivability against interfering signal streams or solar conjunctions. But they nevertheless offer some improvement in robustness by allowing operation during short "grazing" events.

An operational definition of the term "short grazing event" depends on interleaver design and code capability. These parameters may be selected by the system designer or user to achieve necessary performance goals.

The cost of interleaving and coding falls on the user spacecraft and ground terminal equipment. The major weight and complexity penalty is on the receiving side, particularly in the FEC decoder. When coding is employed on forward link communication (i.e., from the ground to a user satellite), the associated power and weight of decoder equipment implies secondary penalties of support weight, solar cell array size and manuevering fuel.

The advantages of interleaving and coding not equivalent to those of increased EIRP or gain. Interleaving/coding attacks the worst error events rather than the average channel (which is likely to be fairly good). On the other hand, interleaving/coding rapdily reaches an implementational limit as error bursts approach 10^5 channel symbols. These techniques should be viewed as complementary, rather than separate means to the same end.

4.6 REGULATORY INJUNCTIONS AGAINST IDENTIFIABLE INTERFERERS

Regulatory remedies can be considered an RFI mitigation technique in a broad system context encompassing social as well as technological elements. In the event of RFI due to U.S. or foreign civilian services, this technique may, in some cases, offer hope of controlling the source of RFI. However, the method's success depends on the unsure outcome of regulatory proceedings. It is wise to consider this recourse during frequency plan development, but unwise to rely on it exclusively.

The regulatory basis for protecting TDAS from RFI emitters lies in assigning TDAS services a higher allocation status in its operating bands than the potential RFI emitters. Showing primary allocation status for TDAS, but only secondary allocation status for the RFI emitter, is the most straightforward. In cases of equal allocation status, precedence in time must be established. The desirability of operating with a primary allocation status is clear--it offers support in the event that regulatory remedies become necessary, and guards against similar proceedings taken against TDAS by other services. In addition to the time-consuming nature of the regulatory process, it requires precise identification of the RFI source. This may not be easy in an operational TDAS, where the emphasis is on service rather than pinpoint electromagnetic sensing. In contrast to technological means of RFI mitigation, which only require characterization of RFI, regulatory proceedings require characterization and identification of the RFI emitter.

4.7 MULTIPLE ROUTING

In a TDAS constellation with three or more satellites, a USAT will frequently view two or more TDAS satellites simultaneously. Some decision-making entity must select one TDAS from several as a support link for the USAT. This choice can be made dependent on known RFI source locations, to avoid main-beam-to-main-beam interactions.

Outages due to solar RFI and self-interference can be predicted on geometric grounds and known equipment performance. In the event of predicted outage, alternative routing will sidestep the RFI geometry. Interference from other civilian and military services can be mitigated as well, although prediction is more difficult since these users may not have formal coordinating channels with the TDAS control system.

4.8 ACCESS DIVERSITY

Access diversity encompasses the techniques of frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access* (CDMA). These techniques are primarily effective against self-interference, since all elements of a self-interference scenario are subject to control. These diversity techniques can be thought of as additional elements in a multiple routing universe. Where alternative routing separates transmissions in space, the diversity techniques addressed here separate transmissions in time or frequency. One potential advantage of access diversity over multiple routing is the fact that main-beam-to-main-beam conflict can exist on a geometric level, without actually degrading performance. This may offer enhanced flexibility to the scheduling algorithms, depending on the diversity implementation selected.

CDMA offers mitigation against narrow band interference, but fails to protect against broadband-noise type signals. In general FDMA and TDMA are vulnerable to external RFI. FDMA and TDMA offer no protection against military RFI. These techniques are also ineffective against solar RFI, since the sun emits radiation continuously at all frequencies. They are similarly

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* Code division multiple access is also known as spread-spectrum multiple access (SSMA), since it operates by a fast binary code multiplied with the unmodulated data stream that spreads the signal energy over a bandwidth much larger than the information bandwidth.

ineffective against non-TDAS civilian services, since these are typically continuous and at frequencies not subject to TDAS control.

4.9 COMMAND VERIFICATION PROTOCOLS

Command verification protocols are error-detecting rather than error-correcting techniques, useful on command transmission but not data transmission. A typical method is for spacecraft A, receiving a command, to echo it back to the transmitter. The transmitting station compares the echo to a stored copy of the original message and transmits a go-ahead in the event of a match. The command is executed when the go-ahead is received by spacecraft A. This protocol approximately triples the command cycle time since three transmissions are involved rather than one. But it guarantees detection of all errors in command transmission. As a result, RFI will never be the cause of uncommanded activity by a spacecraft.

RFI survivability is not achieved, since RFI still enters the communication link and disrupts reception. But robustness is enhanced since inaction is prefered over incorrect action.

The costs of verification protocols are mostly in command delay time. The approximately tripled cycle time may entail degraded performance for realtime control scenarios. For example, ground-commanded antenna pointing and acquisition of a user satellite may become sluggish due to additional delays. This could be resolved by dividing the command set into two classes: commands that require verification and commands that do not. Verifiable commands would typically commit the spacecraft to a critical activity such as a propellent burn, while unverifiable commands would be non-critical, such as initiation of search procedures for a particular user satellite.

An alternative to command classification into verifiable and nonverifiable sets is a capability for more complex decision-making on the satellite, so that a single verifiable command could trigger a complex series of actions without additional ground interaction. This would boost the cost, weight, and complexity of the spacecraft processor.

GLOSSARY

CONUS	Continental United States
E_b/N_o	Energy per bit-to-thermal noise per hertz
EES	Earth-exploration satellite
EIRP	Effective Isotropically Radiated Power
FCC	Federal Communications Commission
ISM	Industrial-Scientific-Medical
J/S	Jammer-to-Signal Ratio
LEO	Low Earth Orbit
NOI	Notice of Inquiry
NTIA	National Telecommunications and Information Administration
RFI	Radio Frequency Interference
SETI	Search for Extraterrestrial Intelligence
TDAS	Tracking and Data Acquisition System
TDRSS	Tracking and Data Relay Satellite System
USAT	User Satellite
WARC	World Administrative Radio Conference

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